A hot compact dust disk around a massive young stellar object

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Circumstellar disks are an essential ingredient of the formation process[1] of low-mass stars such as our sun. However, it is unknown whether the accretion disk paradigm can also account for the formation of stars more massive than ~10 solar masses[2], where strong radiation pressure might halt mass infall[3,4]. For instance, it has been proposed that massive stars might form not by accretion but by stellar merging[5], although more recent theoretical investigations suggest that the radiative pressure limit might be overcome by considering more complex, non-spherical infall geometries[6,7]. Therefore, clear observational evidence, such as the detection of compact dusty disks[8] around massive young stellar objects (YSOs), is needed to unambiguously identify the formation mode of the most massive stars. Here we report on near-infrared interferometric observations, which spatially resolve the AU-scale distribution of hot material in the inner environment around

a high-mass (~20 $M_\odot$) YSO. We reconstruct a model-independent interferometric image which shows an elongated structure with a size of ~13×19 AU, consistent with a disk seen under an inclination of ~45º. Using geometric and detailed physical models, we detect a radial temperature gradient and a dust-free region inside of 9.5 AU from the star, revealing qualitative and quantitative similarities with the disks observed in low-mass star formation. Perpendicular to the disk plane we observe a molecular outflow and two bow shocks, indicating the presence of a bipolar outflow emanating from the inner regions of the system.

We investigated the massive young stellar object IRAS 13481-6124, which harbours a central object of about 20 $M_\odot$[9] embedded in a cloud with a total gas mass of ~1,470 $M_\odot$[10]. Our imaging observations cover wavelengths from 2 to 870 µm and spatial scales from several parsecs to AU. In archival *Spitzer* Space Telescope images[11] (Figure 1a), we discover two faint bow shocks, which are oriented along position angle PA=31±6° and separated by 7', corresponding to a physical scale of ~6.5 pc at a distance of 3,500 pc[12]. In addition, we observed the source with the APEX 12 m sub-millimeter telescope located on Chajnantor plateau in Chile. Using imaging observations in emission lines of molecular gas, we detect a bipolar outflow, which is oriented along the same axis (PA=26±9º, Figure 1b) as the bow shocks. With a relatively narrow bow shock opening angle of ~6°, the detected outflow signatures show similarities with the bipolar collimated jets observed in low-mass star formation. Since outflows from young stars are powered by accretion[13] and require a magnetized, compact accretion disk to collimate the ejected material[14], the detected outflow provides some indirect evidence for the existence of a disk around IRAS 13481-6124.

In order to directly detect this disk and to characterize its inner structure, we employed the *Very Large Telescope Interferometer* (VLTI) of the European Southern Observatory located on Cerro Paranal in Chile. Using the near-infrared beam combination instrument AMBER[15], we combined the light of three of the VLTI 1.8 m telescopes and measured the interferometric observables (visibilities and closure phases) in 17 spectral channels in the K band (λ=1.95–2.55 μm). The VLTI observations were obtained using three different telescope triplet array configurations and are complemented with speckle interferometric observations with the *New Technology Telescope*, providing precise spatial information for baseline lengths ≤3.5 m.

Using our extensive VLTI+speckle data set, we could reconstruct[16] a model-independent interferometric image from the measured visibility amplitudes and closure phases. This technique, which is routinely applied in radio interferometry, has recently also been demonstrated with VLTI[17] and was applied in our study to image the circumstellar environment around a young star. With baseline lengths B up to 85 m, our image provides an angular resolution of $\lambda/2B$=2.4 milli-arcseconds (mas) or ~8.4 AU, which is at least one order of magnitude higher than conventional infrared imaging techniques at 10 m class telescopes, while the gain compared to state of the art (sub-)millimeter disk studies is about two orders of magnitude. The reconstructed image (Figure 1c) clearly resolves the inner environment around IRAS 13481-6124 and reveals a compact elongated structure with a size of 5×8 mas. The disk orientation (PA=120º) is perpendicular to the determined outflow axis (26±9º and 31±6º), suggesting that the AU-scale disk resolved by VLTI/AMBER is indeed the driving engine of the detected collimated outflow.

To further characterize the detected elongated structure, we fitted geometric and detailed physical models to our data, allowing us to deduce object information smaller than the diffraction-limited resolution of our reconstructed image. Our measurements show that the visibility function drops rapidly at baseline lengths < 3 m, but stays then nearly constant up to baseline lengths of about 12 m, followed by a uniform, nearly linear decline at baseline lengths up to 85 m (Figure S10 in the Supplementary

Information), providing clear evidence for the presence of at least two spatial components. We use a Gaussian model to estimate the characteristic size (FWHM diameter) of the two components and find that the first, extended component has a size of about 108 mas and contributes ~15% of the total flux. Based on the finding of scattered light envelopes around other massive stars[18], we suggest that this extended, centro-symmetric component is the scattered light contribution of a natal envelope. The second, compact component has a size of 5.4 mas and accounts for 85% of the total K band flux and is significantly elongated along position angle PA=114º. Furthermore, we find that the size of the compact component increases significantly towards longer wavelengths (as shown by the measured equivalent widths in Figure 2a). This effect, which was found towards many low- and intermediate-mass YSO disks[19,20], is likely indicating a temperature gradient in the circumstellar material, where hotter material (radiating more effectively at shorter wavelengths) is located closer to the star.

Motivated by these indications for an internal temperature structure, we fitted analytical disk models with a radial temperature power-law, $T(r)=T_{in}\,(r/r_{in})^{-q}$, to our data. Assuming reasonable values for the inner disk temperature, i.e. T_{in}=1,500 to 2,000 K, we find that this model can reproduce our interferometric data with an inner disk radius r_{in} of 3 mas (9.5 AU), and a temperature power law index q of 0.4, which is consistent with the theoretical temperature gradient[21] of flared irradiated disks (q=0.43). Compared to other geometric models or disk models with emission extending to the star, this disk model provides a significantly better representation of our data (see Figure 2b and Section S4 for more details). Intriguingly, the derived inner disk radius of 9.5 AU agrees with the expected location where dust in an irradiated circumstellar disk would sublimate, i.e. 6.2 AU to 10.9 AU assuming grey dust and dust sublimation temperatures between 2,000 and 1,500 K. Therefore, IRAS 13481-6124 is following the size-luminosity relation[22], which is well established for low- to intermediate mass

YSOs, suggesting that the near-infrared emission mainly traces material at the dust sublimation radius, similar as in the disks around T Tauri and Herbig Ae/Be stars.

Besides the rather general arguments presented above, we performed a detailed physical modelling using multi-dimensional continuum radiative transfer simulations. Including the central star, disk, and envelope, these models can provide a much more comprehensive and consistent picture of the IRAS 13481-6124 system. Given that these models depend on many free parameters, we employed a pre-computed grid of radiative transfer simulations[23] and an associated SED-fitting tool[24] in order to find a good initial set of model parameters. Using an adopted version of the radiative transfer modeling code by Whitney et al.[25] we further refine the model parameters and find a model that can reproduce the SED and the VLTI+speckle observations simultaneously, yielding the model image shown in Figure 1d (see Figures S13 and S14 for visibilities, closure phases, and the SED and Table S4 for the complete set of model parameters). Our global best-fit model parameters suggest a distance of 3,260 pc and include a central star with a mass of 18 $M_\odot$, a massive (1,000 $M_\odot$) circumstellar envelope with a bipolar curve-shaped outflow cavity, and a compact (~130 AU) flared disk with a similar mass as the central star (20±8 $M_\odot$). Many model parameters, for instance concerning the envelope geometry and the total dust disk mass, may still suffer from the well-known parameter ambiguities, which are inherent to SED fitting results[24]. Other parameters, such as the inner disk radius and the disk orientation, are for the first time constrained by spatially resolved observations. One particularly interesting property of the resolved disk is the lack of asymmetry, which is evident from the measured small closure phases, and which also reflects in the rather symmetric reconstructed image. For our radiative transfer models, this low degree of asymmetry provides direct constraints on the vertical disk structure near the dust sublimation region and suggests a rather smooth shape of the inner dust rim. Equivalent to the findings for intermediate-mass stars, this likely indicates that the inner dust rim around IRAS 13481-6124 has a curved geometry (see also Sections S3 and S5), although more theoretical as well as observational work is needed to ultimately characterize the detailed inner rim geometry. In particular, future observations using mid-infrared and sub-millimeter interferometers could resolve the inner disk structure over a very wide wavelength range, providing additional constraints on the radial density structure and the more extended disk regions.

The measured low degree of asymmetry is also interesting in the context of numerical simulations of self-gravitating disks, which predict the formation of large-scale spiral density waves[8,26] and a highly non-axisymmetric disk structure. Given that these asymmetries are not detected by our VLTI phase closure observations, we conclude that these processes are not dominant in the probed inner regions of the IRAS 13481-6124 disk or are not sufficiently resolved. Also, our speckle and VLTI data rules out the presence of nearby stellar companions (down to flux ratios of ~1:40 and separations $\geq$10 mas), contrasting with the prediction of compact stellar clusters in competitive accretion and stellar merger models[27]. Concerning the evolutionary state, our observations suggest that IRAS 13481-6124 has already gone through its main accretion phase and that the disk gains most of its heating by stellar irradiation. This conclusion is supported by the derived disk structure, which closely resembles the irradiated dust disks around Herbig Ae/Be stars, but is distinctively different from the actively accreting disks observed, for instance, around FU Orionis stars. According to our radiative transfer model and the underlying stellar evolutionary tracks[28], the system has an evolutionary age of $\sim 6\times10^4$ yrs, roughly matching the expected age of 10^5 yrs when disk evaporation should start[29]. Therefore, we likely observe the system in a short-lived phase, where the strong stellar winds, radiation pressure, and photoevaporation have already stopped accretion, and are just starting to dissipate the circumstellar disk.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions S.K. worked on the AMBER data reduction and data interpretation, model fitting, image reconstruction, performed some of the observations and wrote the telescope proposals and the initial paper manuscript. K.-H.H. worked on the image reconstruction. D.S. worked on the speckle data reduction. G.W. performed some of the observations. F.W. worked on the APEX data reduction and data interpretation. K.M. and P.S. were co-authors on the telescope proposal. A.M., K.P., R.P., S.R.-D. and L.T. are representing the AMBER instrument consortium, which has provided some parts of the observing time. All authors commented on the paper.

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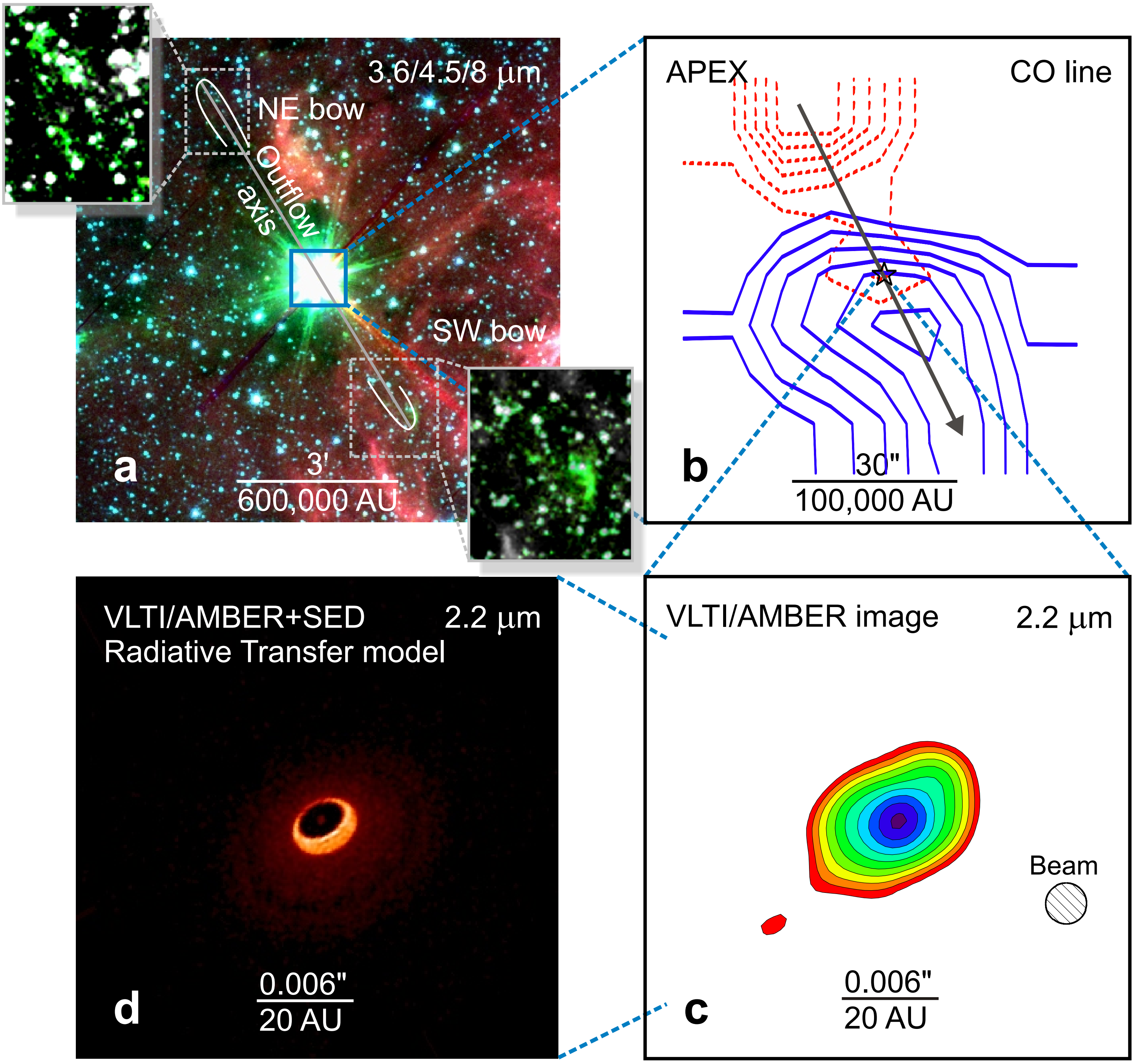
Figure 1: **Zoom in on IRAS13481-6124, covering structures over more than five orders of magnitudes. a,** In *Spitzer*/IRAC images, we detect two bow-shock structures, indicating a collimated outflow. The bows are separated by 7' and appear as excess emission in the IRAC 4.5 μm band (coded as green), likely tracing shocked molecular hydrogen gas[30]. **b,** The outflow is also detected in molecular line emission using APEX/SHFI on scales of a few 10,000 AU with the approaching (blue-shifted) lobe southwest of IRAS 13481-6124 (contours show a blue-shifted velocity of -10 km/s and a redshifted velocity of +5 km/s). As outflow tracer line, we used the ^{12}CO (3-2) line at 867 μm. **c,** VLTI/AMBER aperture-synthesis imaging reveals an elongated structure, which is oriented perpendicular to the outflow direction (contours decrease from peak intensity by factors of $\sqrt{2}$). The structure has a size of 5×8 mas, as measured at 10% of the peak flux intensity, and contributes about 4/5 of the total flux in the image, while the remaining flux elements are spread rather uniformly over the image and correspond to the extended component detected in our model fits. The image was reconstructed from an extensive data set of 33 independent VLTI/AMBER three-telescope observations, including three different 3-telescope array configurations. **d,** Best-fit radiative transfer model image as constrained by the measured wavelength-dependent visibilities and closure phases and the SED from near-infrared to millimeter wavelengths (see also Figures S13 & S14). This modelling allows us to determine the intensity profile on scales smaller than the diffraction-limited resolution and strongly suggests that the dust disk is truncated at a radius of 6.2±1.2 AU.

Figure 2: **Elongation of the compact emission component, as determined with a Gaussian and a temperature gradient disk model. a,** Using a Gaussian model, we determine the object size for different position angle bins (each covering 10°) and wavelength channels centered on 2.1 μm (blue), 2.3 μm (green), and 2.5 μm (red), revealing a strong object elongation and indications of a temperature gradient. The shown error bars give the standard deviation. **b,** Using a temperature power-law disk model $T(r)=2{,}000\ K\ (r/r_{in})^{-q}$, we determine the temperature power-law index q to ~0.4 and find an ellipsoidal source geometry, corresponding to a disk seen under an inclination angle of ~45°. The truncated dust disk model yields a significantly better representation of the measured wavelength-dependent visibilities (χ^2/dof=1.1) than standard geometric models (e.g. Gaussians, χ^2/dof=2.5; see Section S4).


3.6/4.5/8 μm
NE bow
Outflow
axis
SW bow
a
3'
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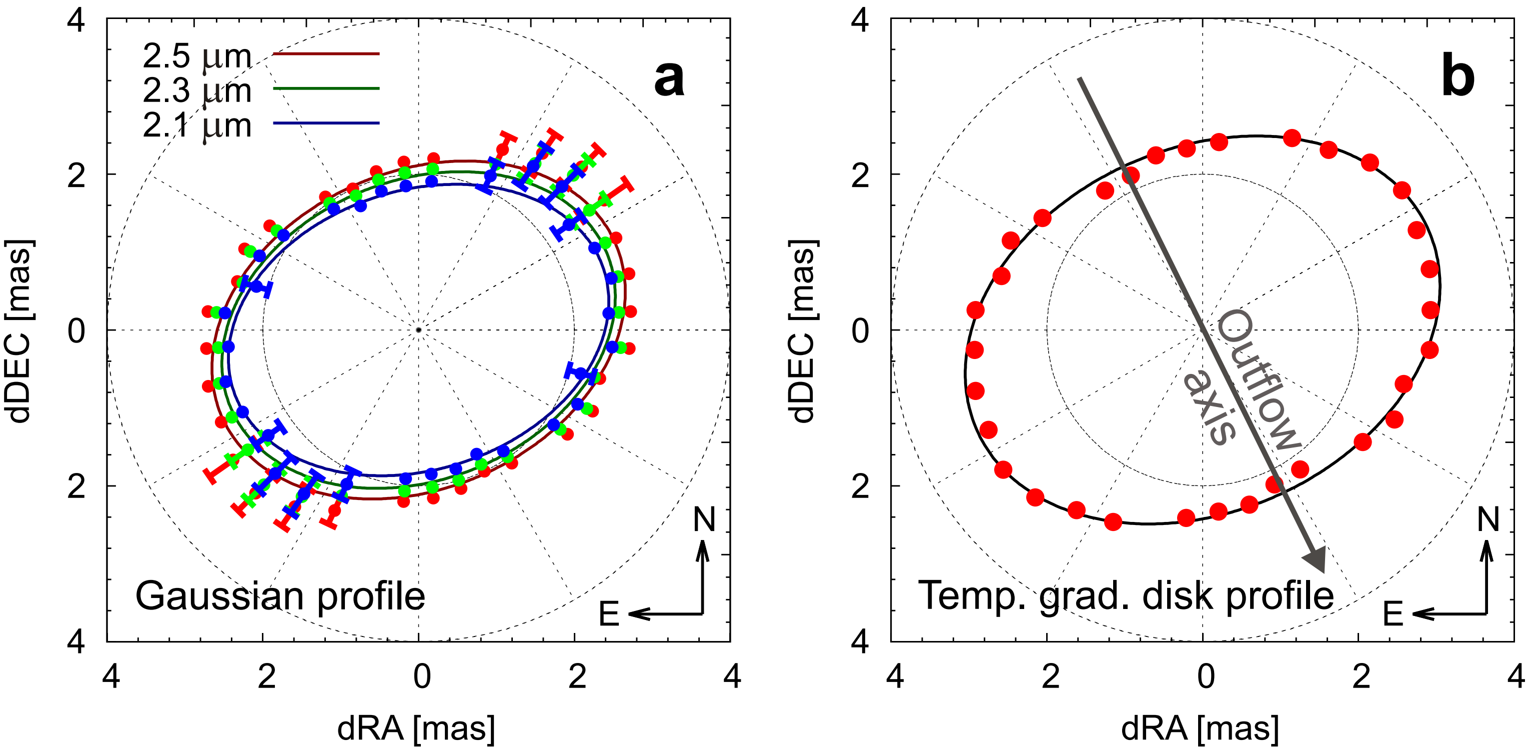
APEX
CO line
b
30"
100,000 AU
VLTI/AMBER+SED
2.2 μm
Radiative Transfer model
d
0.006"
20 AU
VLTI/AMBER image
2.2 μm
Beam
c
0.006"
20 AU



2.5 µm
2.3 µm
2.1 µm
a
Gaussian profile
dDEC [mas]
dRA [mas]
N
E
b
Outflow axis
Temp. grad. disk profile
dDEC [mas]
dRA [mas]
N
E