STRUCTURES IN THE PROTOPLANETARY DISK OF HD142527 SEEN IN POLARIZED SCATTERED LIGHT

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ABSTRACT
We present H- and Ks-band polarized differential images (PDI) of the Herbig Ae/Be star HD142527, revealing its optically thick outer disk and the nearly empty gap. The very small inner working angle (∼0.1") and high resolution achievable with an 8m-class telescope, together with a careful polarimetric calibration strategy, allow us to achieve images that surpass the quality of previous scattered light images. Previously known substructures are resolved more clearly and new structures are seen. Specifically, we are able to resolve 1) half a dozen spiral structures in the disk, including previously known outer-disk spirals as well as new spiral arms and arcs close to the inner rim of the disk; 2) peculiar holes in the polarized surface brightness at position angles of ∼0° and ∼160°; 3) the inner rim on the eastern side of the disk; 4) the gap between the outer and inner disk, ranging from the inner working angle of 0.1" out to between 0.7 and 1.0", which is nearly devoid of dust. We then use a Markov-chain Monte-Carlo algorithm to determine several structural parameters of the disk, using very simple assumptions, including its inclination, eccentricity, and the scale height of the inner rim. We compare our results to previous work on this object, and try to produce a consistent picture of the system and its transition disk.

Subject headings: stars: pre-main sequence — stars: formation — protoplanetary disks — planet-disk interactions — stars: individual (HD142527)

1. INTRODUCTION
Understanding the initial conditions and dominant physical processes of planet formation is vital to explaining the diversity of planetary system architectures observed. This requires the study of circumstellar disks.
The search for and investigation of young stars and their protoplanetary disks has a long history and has been carried out in a variety of different wavelengths. Besides ultraviolet studies, which can be used to measure the accretion rate of the central star, two important regimes can be distinguished: The thermal emission of the disk, and the reflected light. Thermal emission can be used to determine the dominant constituents of a disk through spectroscopy, and it can be used to image the disk, with the short wavelengths tracing the hot, inner material of the disk and the long wavelengths tracing the colder material further out. At short wavelengths (≪5μm) and large separations (> a few AU), the light from the disk is dominated by the stellar light scattered off the dust grains. This does not depend on the temperature of the grains, but on their scattering properties. Last but not least, molecular line tracers, mostly in the (sub-)mm, can give us information about the gas rather than the dust in the disk, so we have a rich set of tools to study these circumstellar, planet-forming environments. Unfortunately, the Herbig Ae/Be and T-Tauri stars harboring them are typically located at 100pc or more from the sun, which means that the physical separations where most planets form (≪50 AU) translate to angular separations of 0.5" or less. Probing this regime at high resolution is difficult both in scattered light and thermal emission. In scattered light, PSF (point spread function) subtraction and coronagraphs are often used to block the stellar light, but while this is an excellent tool for studying the outer parts of such disks, the inner working angle is typically not good enough to probe the circumstellar environment at separations smaller than 0.5-1" (e.g. Grady et al. 2001; Fukagawa et al. 2010; Casassus et al. 2012). On the other hand, the ratio of stellar to disk flux is much more favorable in the far-infrared and sub-mm regime, but the telescope resolution criterion usually severely limits the achievable resolution, though ALMA (Wootten & Thompson 2009) brings dramatic improvements here.
Polarimetric differential imaging (PDI) is a powerful technique to suppress the stellar light in scattered light observations and has recently been successfully applied to several protoplanetary disks (e.g., Quanz et al. 2011; Hashimoto et al. 2011; Muto et al. 2012; Quanz et al. 2012; Hashimoto et al. 2012; Tani et al. 2012; Kusakabe et al. 2012; Mayama et al. 2012; Grady et al. 2013; Quanz et al. 2013; Garufi et al. 2013). It uses the fact that while the light from the central source is largely unpolarized, scattering on the dust grains in the disk produces polarization. PDI allows to probe the circumstellar environment of young stars very close to the star and achieve the high contrast ratios required to detect their circumstellar disks.
In this paper, we present H- and Ks-band PDI observations of HD142527 with an inner working angle of less than 0.1" (∼15 AU), revealing the large gap in scattered light.
light in unprecedented clarity and showing the outer disk in unprecedented detail, including several previously unrecognized spiral arms and gaps. We discuss our results, present estimations for the basic parameters of the disk using an Markov-chain Monte-Carlo code and link our findings to the current knowledge about this extraordinary disk.

The paper is structured as follows: In section 2, we describe the HD142527 system in general. In Section 3, we give a short introduction to the observations and data reduction. We present the results in Section 4, followed by an analysis of these results in Section 5. In Section 6, we discuss our findings and compare them to earlier studies. We draw our conclusions in Section 7. A detailed description of our data reduction pipeline, which has also been used for the data reduction of our observations of HD169142 and SAO206462 (Quanz et al. 2013 Garufi et al. 2013), is given in the appendix.

2. THE HD142527 SYSTEM

HD142527 is an F-type Herbig Ae/Be star (Waelkens et al. 1996) that has been classified as group Ia (Meeus et al. 2001), meaning that its spectral energy distribution (SED) rises in the mid-IR and also shows a 10μm silicate emission feature. It further shows signatures of water ice (Malfait et al. 1999) Honda et al. 2009. The circumstellar environment consists of an inner and outer disk separated by a gap which has been detected in the mid-IR and from sub-mm continuum observations. While the inner border of the outer disk is well-constrained at ~130 AU and is eccentric, the extent of the inner disk is observationally less constrained and has been modeled to have a radius of ~30 AU, and potentially being surrounded by a halo (Verhoeff et al. 2011) Casassus et al. 2013. The inner disk is highly crystalline and is responsible for the mid-infrared emission (Leinert et al. 2004) van Boekel et al. 2005. The outer disk is responsible for most of the far-IR emission and optically thick at near- and mid-infrared wavelengths. It is highly structured and asymmetric and has been studied in scattered light in the near-IR H-band, $K_s$-band, and $L$-band (Fukagawa et al. 2006) Rameau et al. 2012 Casassus et al. 2012. Recently, a PDI study by Canovas et al. 2013 revealed the outer disk in polarized light and also showed the outer regions of the gap, without being able to detect the inner disk.

HD142527 has an extraordinarily high infrared flux compared to the stellar flux ($F_{IR}/F_\star = 0.92$ Domink et al. 2003), which has been explained by Verhoeff et al. 2011 with an unusually large scale height of the outer disk. Planetary-mass companions have been suggested multiple times to explain the eccentric shape of the outer disk, but direct searches for such companions using angular differential imaging have yielded null results (Rameau et al. 2012 Casassus et al. 2013). However, Biller et al. 2012 suggest a stellar companion (0.1-0.4 M$_\odot$ at ~0.085") based on Sparse Aperture Masking observations. The validity of this claim is unclear (Casassus et al. 2013). A recent study of the system with ALMA (Casassus et al. 2013) suggests that material from the outer disk is falling onto the inner disk via streamers through the gap, consistent with measured accretion rates onto the star (Garcia Lopez et al. 2006). It also reveals a large asymmetry in the sub-mm continuum flux, possibly produced by a Rossby wave instability like the one shown for IRS 48 by van der Marel et al. 2013. The ALMA radial velocity data for HD142527, combined with the assumption that the spiral arms are trailing, also supports the suggestion by Fujitara et al. 2006 that the eastern side is the far side of the disk.

The parameters of the HD142527 system are summarized in Table 1. We adopt a value of 145 pc for the distance to the star because it is likely a member of the Upper Sco association (Acke & van den Ancker 2004) de Zeeuw et al. 1999). The value of 145 pc is well within the 3σ error margin of the Hipparcos measurement (van Leeuwen 2007).

3. OBSERVATIONS AND DATA REDUCTION

The observations were performed on the night of July 23rd, 2012 with the NAOS/CONICA (NACO) instrument of the Very Large Telescope (VLT) at Cerro Paranal, Chile, in the H and $K_s$ filter. Because HD142527 is bright enough to saturate the detector at the shortest possible integration time (0.345s), additional unsaturated images were taken in the narrow-band NB1.64 and NB2.17 filters. The total on-source integration times were 2860s and 2984s, respectively, in the H and $K_s$ filters, and 340s / 187s in the respective narrow-band filters. We did not observe any calibration stars, but use the central star itself for calibration. The observing conditions were mostly favorable with an average seeing in the optical of 1.04" during the H band observations and 1.21" during the $K_s$ band observations. The coherence time was 2ms or longer. The conditions during the narrow-band filter observations were slightly worse. Sky conditions were photometric and the airmass did not exceed 1.17. A summary of the observations is given in Table 2.

We used the SL27 camera (pixel scale of 27 mas
structures in the protoplanetary disk of HD142527 seen in polarized scattered light

4. RESULTS

Figure 1 shows the $P_{\perp}$ images obtained by our reduction along with a polar coordinate mapping of our results. The disk is clearly seen at high signal-to-noise ratio (SNR) in both filters in $P_{\perp}$. The $P_{\parallel}$ images show mostly noise and faint residuals that are different between the two filters at the position of the disk. They do not show any clear or consistent structure and are not shown here (an example can be found in the appendix). The disk is clearly not symmetric, as already previously observed.
The disk itself displays a complex spiral arm structure, which we trace in Figure 1 d). Two of these spiral arms (S1 and S2) have been detected before (Fukagawa et al. 2006; Casassus et al. 2012), S5 has also recently been seen by Canovas et al. (2013). The others are new detections. We are able to resolve the eastern side of the disk much more clearly, which also shows spiral structures. In the north (PA $\sim 0^\circ$) and southeast (PA $\sim 160^\circ$), significant holes (lack of polarized flux) are seen in the disk.

As can be seen in Figure 1 c), these holes seem to extend outwards, almost as if they were casting shadows. Interestingly, there is one spiral arm (S3) which passes through the northern hole and re-appears on the other side of the hole. These holes have been hinted at before (e.g. Fukagawa et al. 2006; Rameau et al. 2012; Canovas et al. 2013), but not been seen at this resolution.

In Figure 2, we trace the surface brightness of the disk in the North, East, South and West direction. The disk shows a similar brightness in the eastern and western direction in polarized scattered light, in contrast to unpolarized scattered light, where the western side is brighter (Fukagawa et al. 2006). The disk reaches its peak brightness of $\sim 11.7$ mag $\arcsec^{-2}$ in $H$ band and $\sim 10.8$ mag $\arcsec^{-2}$ in $K_s$ band in the northwest, at a position angle of $\sim 330^\circ$. Compared to the 2MASS $H - K_s$ color of the star, the scattering is slightly red (by $\sim 0.16$ magnitudes). Further out, the surface brightness drops rapidly. Fitting power-laws to the outer parts of the disc (outside $1.2''$) leads to the following results for the power-law exponent in $H$ / $K_s$ band: North: $-8.6 \pm 1.2 / -6.2 \pm 0.7$; South: $-7.0 \pm 0.6 / -6.1 \pm 0.3$; East: $-6.8 \pm 0.2 / -6.6 \pm 0.4$; West: $-4.5 \pm 0.2 / -4.5 \pm 0.2$. It is worth noting that starting from $1.2''$ usually ignores the inner spiral arms.
It also ignores the northern hole, which strongly affects the surface brightness in the northern direction between 0.8" and 1.2". The surface brightness profiles are somewhat steeper in the $H$ band compared to the $K_s$ band, especially in the northern and southern direction. However, this result has to be taken with care as the number of points usable for the fit in the northern and southern direction is limited by the polarimetric mask.

To measure the fractional polarization of the disk, we need a direct measure of the total scattered light. In the case of HD142527, the scattering from the disk is so strong that it can be seen directly in the intensity images we obtained, without a coronagraph or PSF subtraction - even in the individual frames. Because of this, we extract the information about the (non-polarized) scattered light directly from our data, rather than taking literature information, because we are then using the same dataset taken at the same time, which is less prone to errors.

During our observation run, we did not only observe HD169142 (Quanz et al. 2013), SAO206462 (Garufi et al. 2013) and HD142527 (this paper), but also HD141569 and HD163296. Both these objects are known to harbor disks (e.g. Weinberger et al. 1999, Grady et al. 2000), which however we did not or just barely detect, meaning that we essentially see the point spread function (PSF) of the star. The disk of HD169142 is rather weak, and the intensity image is also dominated by the PSF of the star, the directly measured polarization does not exceed 2% anywhere in the image. Furthermore, it is fairly symmetric in shape.

This means that we have three PSF reference stars at our disposal, and in our case we have the additional knowledge that the inner part of the disk (out to ~0.6") is nearly empty. Thus, by subtracting a linear combination of the reference star intensity images, we try to minimize the flux in this inner region. We use the HD169142, HD163296 and HD141569 $H$ band images for the $H$ band subtraction, and the HD169142 and HD141569 $H$ band images for the $K_s$ band subtraction (we did not obtain $K_s$ band images for these, and the HD163296 $K_s$ band image is a very poor fit). We emphasize that this is not the ideal way to perform a PSF subtraction, especially because the other stars are known to harbor disks, but we opt for this way because we can use the same data for both the intensity and the PDI images.

We show our results in figure 3. As can be seen, the subtraction works significantly better in the $H$ band than in the $K_s$ band. The measured polarization fractions are between ~20% in the western (forward-scattering) part and ~45% in the eastern (backward-scattering) part of the disk.

The intensity and polarization fraction images are plagued by various artifacts. For example, the spider pattern gets incorrectly over-subtracted, especially in the northern hole region, thus we deem the polarization fraction measurement not reliable in this region. There are several more artifacts seen, which do not represent real structures in the disk. We also emphasize that while there is a difference seen between the $H$ and $K_s$ image, we do not think that this is significant, but is likely a result of the bad subtraction in the $K_s$ band. The difference between the eastern and western sides of the disk, however, is significant and consistently detected in both filters.

We also compare the flux measured in the $H$ and $K_s$ bands to determine the color of the disk. In general, the disk is slightly red: The total flux of reflected polarized light compared to the stellar flux $\frac{F_{\text{int}}}{F_\star}$, within our field of view is $(7.1\pm0.3)\times10^{-3}$ in $H$ band and $(8.2\pm0.3)\times10^{-3}$ in $K_s$ band, hinting towards relatively large grains (c.f. Mulders et al. 2013). The color of the disk is not constant, though: In the eastern and western part it appears to be more blue than in the north and south (figure 1). It is unlikely, though not impossible, that this pattern stems from the data reduction. A problem in the data reduction would likely manifest in an 8-leaf pattern (4 positive, 4 negative leaves) rather than in a 4-leaf (2 positive,
5. ANALYSIS

5.1. Disk gap

It has been known for a while that between the massive, optically thick outer disk and the small inner disk, there is a large gap (Fukagawa et al. 2006; Casassus et al. 2012). In our images, the surface brightness drops dramatically inside the inner rim of the outer disk (c.f. figure 2). While just inside the outer disk, weak scattered light is still present, we do not detect scattered light at the 3σ level inside of 0.4″ around the star. This also means that we do not detect any trace of the inner disk or halo of the system down to our inner working angle of 0.1″.

To assess the amount of dust that can still be present in the gap below our detection limits, we would need to know the scattering properties of the dust grains, specifically their albedo and their polarization efficiency at the respective scattering angle. Because we do not want to rely on models, we use our data to derive lower limits for the product of the two (called AP here), which we then turn into upper limits for the optical depth perpendicular to the disk plane. Because we take the outer, optically thick disk, where multiple scattering and self-shadowing effects will lower the albedo and the polarization efficiency and thus AP, this approach is conservative.

Assuming a dust particle of radius r at a distance of R from the star, the polarized flux due to scattering from the dust particle is:

$$F_d = F_\star \frac{\pi r^2}{4\pi R^2} (AP)$$

where A is the albedo and P is the polarization efficiency of the particle. Both depend on the scattering angle, but in our case the disk is close to face-on (∼20°, Pontoppidan et al. 2011; Verhoeff et al. 2011), and we neglect inclination effects for this first-order estimate. In this form, this only holds true for single particles. However, if we add in the geometric fill factor of the dust (defined as $f_{geo} = 1 - 1/e^2$), we can use this formula for patches on the sky:

$$F_d \leq F_\star \frac{S f_{geo}}{4\pi R^2} (AP)$$
were $S$ is the area of the patch on the sky we observe. We use the inequality because, as stated above, multiple scattering and self-shadowing effects can reduce the polarized flux. We can turn this into a calculation for $AP$: and thus:

$$AP \geq \frac{4\pi R^2 F_d}{F_\star S_{geo}}$$

(8)

We realize that the geometric filling factor cannot be larger than unity. Furthermore, the distance in the image plane provides a lower limit to the actual physical distance, and we use this formula to provide a lower limit for $AP$. To do so, we evaluate the formula above across the whole image frame and search for its maximum. The derived lower limits for $AP$ are 4.1% in the H band and 5.1% in the $K_s$ band, consistent with previously estimated albedos (e.g. Mulders et al. 2013) and the polarization efficiencies determined in section 4.

We turn these lower limits for the albedo and polarization efficiency into upper limits for the optical depth $\tau$ of the dust, by using the formulas above in reverse or-
over the image of the disk (H band data). The red dots mark our tracing of the inner rim, taking into account the smearing of the inner rim by the PSF.

We see that the gap is very devoid of dust. It is very likely that some dust is present in the gap, because we know that there is an optically thick CO disk filling the entire gap (Casassus et al. 2013). This gas is likely to have been explained in terms of hydrostatic equilibrium by Verhoeff et al. (2011), these authors also suggest that the halo and inner disk extend out to ∼30 AU. In our observations, we do not detect the inner disk at radii down to 0.1″. This means that the inner disk / halo probably does not extend this far out, but resides inside of ∼15 AU, because otherwise we should have detected it.

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do not see any structure inside the gap. This means that we also do not see any streamers of small grains that might corresponding to gas falling onto the inner disk from the outer one, as discussed by Casassus et al. (2013). Our results in this respect are consistent with the results by Canovas et al. (2013), the only other attempt so far to detect scattered light at very small separations for HD142527.

There has to be some clearing mechanism that empties the gap. While photoevaporation can explain holes up to ~20 AU in accreting and even larger holes for non-accreting disks (Owen et al. 2011), it cannot explain the gap in HD142527, which has an accretion rate of 6.9 \times 10^{-8} M_\odot yr^{-1} (Garcia Lopez et al. 2006) and a very large hole. Photoevaporation would also not explain why there should still be an inner disk, which would be expected to clear on a viscous timescale of $t_{\text{visc}} \sim 10^4$ yr. Dust grain growth is an unlikely explanation for the gap because the it is also seen in the sub-mm (Casassus et al. 2013), meaning that the surface density of ~nm-sized grains is low. Chiang & Murray-Clay (2007) show that MRI could grow an existing inner gap, but Dominik & Dullemond (2011) point out that ongoing accretion could still pull significant amounts of dust into the gap, which we do not detect. Also, in this case, there still is the inner disk. Biller et al. (2012) interpret asymmetries in sparse aperture masking observations in terms of a stellar companion at a distance of 88±5 mas (~13 AU) and with a mass of of 0.1-0.4 $M_\odot$. An alternative explanation for their measurements could be an asymmetry in the inner disk responsible for most of the near-IR flux (Casassus et al. 2013). While our data do not allow us to confirm or refute either claim since they only reach in to ~0.1", we can discuss how a companion would affect the gap. According to Artymowicz & Lubow (1994), a binary can clear a circumbinary disk out to a maximum of ~2-3 semimajor radii, with binaries closer in mass and high eccentricities producing larger gaps. Assuming a semimajor axis of 13 AU for the companion, this is incompatible with the semimajor axis of the inner rim of ~140 AU. The claimed companion could only explain the radius of the gap in the unlikely case of a much larger semimajor axis and a highly eccentric orbit ($e \gtrsim 0.7$) combined with having observed it near the pericenter. It is worth noting that in the case of GG Tau A, a young binary system with a derived semimajor axis of 32.4 AU, the binary alone can also not explain the large inner radius of the outer disk of ~180 AU, even though the mass ratio ($\mu=0.47$) is more favorable for a large hole than in the case of HD142527 and the eccentricity of $e=0.34$ is substantial (Beust & Dutrey 2005).

Because of this, we deem the most likely explanation for the large gap to be one or more planetary-mass companions which clear out most of the gas and dust in this region. This also is in concordance with the relatively sharp inner edge of the disk. Casassus et al. (2012) have shown that a single planet could be able to produce a large, eccentric cavity for the disk of HD142527. Their simulation assumes a planet of 10 $M_J$, which is not consistent with the detection limits of Rameau et al. (2012), but Hosseinziborot et al. (2007) show that also lower mass planets can clear eccentric gaps. Such a planet is still feasible even if the proposed stellar companion by Biller et al. (2012) is real. Using the derivations of Holman & Wiegert (1999) and assuming an eccentricity of $e=0$ and a mass ratio of $\mu=0.1$, planetary orbits should be stable outside of ~25 AU (~0.18")

The outer disk is known to be very asymmetric in the sub-mm tracing mm-sized particles. A large horseshoe is seen in the northern direction of the disk, while in the south, the thermal emission is depleted by a factor of ~40 w.r.t. the north (Casassus et al. 2013). While eccentric disks can show a certain degree of asymmetry due to a "traffic jam" effect at the pericenter, this factor is much too large to be explained by this effect. The enhancement is also at the apocenter rather than the pericenter of the disk, and can be much better explained by a vortex, which leads to a dust concentration at the azimuthal pressure maximum and facilitates grain growth and thus planet formation (Regaly et al. 2012; Ataiee et al. 2013).

In this context, the two holes in the disk in the north and southeast are very intriguing. They have also been seen by Casassus et al. (2012) in the $L'$, $K_s$ and $H_2$ bands. Rameau et al. (2012) also see the two holes in $L'$ band. In both cases, the hole was not as clearly resolved. It was not seen as a circular structure, as in our images, but rather as a depletion in the ring of scattered light that could be seen. However, this makes it clear that the structure we see is not due to a depolarization effect, but it is also present in unpolarized scattered light. We also detect it in our PSF subtraction analysis (see figure 3). The location of the northern hole coincides with the location of the probable vortex. This could lead to two possible explanations: One where the small dust is depleted because of growth into larger dust particles, and the scattering at near-infrared wavelengths would be strongly suppressed. The other possible explanation is that a planet has already formed, and is causing the disk surface to bend inwards, and thus to lie in the shadow. Jang-Condell (2009) has shown that this effect could be seen at near-infrared wavelengths, albeit at smaller separations. There is also an asymmetry in the mid-infrared thermal emission. Verhoef et al. (2011) see emission peaks at position angles of +/- 60° and speculate that a planetary-mass object at a P.A. of ~0° could be responsible for a buildup of material at the Lagrange points. Rameau et al. (2012) have estimated mass limits for planets that might be hidden in these both gaps (5 $M_J$ in the northern and 4 $M_J$ in the southeastern gap), so any companion in these would have to be smaller than this.

We adopt a model of the disk with an eccentric, inclined inner rim and constant inner rim scale height. The parameters we estimate for this model are well constrained due to the high signal-to-noise ratio and the high resolution of our images. The two parameters not well constrained (inclination and scale height) are strongly correlated. If we compare our results to the results of Verhoef et al. (2011), we see that they differ. First, they use an axi-symmetric model, i.e. zero eccentricity. Their model uses an inner radius of 130 AU and an outer radius of 200 AU. We determine a semi-major axis of 143±3 AU, but the disk is closer to the star at some points due to the eccentricity. We also want to emphasize that we can trace the disk to distances of more than 300 AU in the eastern and western direction (c.f. figure 2). The inclination and scale height they use (20°, 60 AU) are marked in figure 6 and are consistent with our results.
at the 1σ level. We stress at this point that an accurate measurement of the inclination, for example from rotation curves, would help a lot to break the degeneracy between scale height and inclination. Unfortunately, neither Verhoeff et al. (2011) nor Casassus et al. (2013) provide an error estimate for their inclination determination of 20°. Pontoppidan et al. (2011) provide an error estimate of 20±2°, but this is based on the assumption that $M_\star = 3.5M_\odot$. If the true mass of the star is lower (c.f. Table 1), the inclination would be higher, and the respective scale height would be lower.

The polarization fraction of the disk varies strongly between the eastern and the western side. While it is around 20% on the western side, it seems to be as high as 45% in the east. Due to our reduction technique, we expect the error on the second number quoted to be high (the disk is faint and close in, the region is dominated by the stellar PSF). However, we can see that while the two sides are of comparable brightness in polarized reflected light, it has been seen before that the western side is significantly brighter in scattered light (Fukagawa et al. 2006), a feature which we also detect. We conclude that in fact, the polarization fraction does vary strongly within the disk, with the eastern side being more strongly polarized. One reason for this could be the different scattering angles between the western side (which is closer to us) and the eastern side (which is further away). A fractional polarization of this magnitude and a discrepancy between the forward- and backward-facing side are not unusual for protoplanetary disks and has been observed in AB Aurigae before by Perrin et al. (2009). The difference between forward- and backward-scattering polarization efficiency is consistent with the scattering theory presented in their paper, so we conclude that this is a likely explanation, but detailed modeling in future work will be required to disentangle geometry effects from dust scattering properties.

7. CONCLUSION

In this paper, we image the disk of HD142527 at unprecedented signal-to-noise ratio and resolution. We achieve an inner working angle of 0.1″ and trace the disk out to more than 300 AU in the eastern and western direction, identifying a large amount of substructure in the disk. We also infer the amount of scattered light via a crude PSF subtraction using other target stars in order to determine the fractional polarization of the scattered light and determine the color of the disk. We use an MCMC code to determine the basic parameters of the inner rim of the disk.

Our key findings are:

1. There is a large amount of structure present in the outer disk. We count at least six spiral arms, and there are two prominent holes seen in the disk.

2. The gap between the (unseen) inner disk and the massive outer disk is large and mostly empty. We detect only faint, if any, scattering in the inner region and demonstrate the perpendicular optical depth to be at most $\sim 0.01$. We also do not detect any small-grain correspondence to the gas "streamers" suggested by Casassus et al. (2013).

3. Using an adaptive MCMC code, we determine six basic parameters for the inner rim of the outer disk: Inclination (2 parameters), eccentricity (2 parameters), semi-major axis and scale height. Most of these are very well constrained, with the exception of scale height and inclination. These are very strongly correlated, and an improved measure of the inclination would improve our measurement of the scale height. Our results are compatible with existing models (Verhoeff et al. 2011). For the first time, we measure the scale height of a disk directly from an image.

4. Our geometrical analysis shows that in the eastern (far) side of the disk, because of the very large scale height and the slight inclination, we are actually looking onto the inner wall of the disk.

5. The polarization efficiency in the disk is larger in the eastern (far) side of the disk than in the western (near) side. This is consistent with scattering theory and previous results (Canovas et al. 2013), although we measure a significantly higher polarization fraction of $\sim 20\%-45\%$.

6. The average color of the disk is slightly red between the H and K$_s$ band. There seem to be small, so far unexplained color differences within the disk. Especially, the disk seems to be more red in the direction of the northern and southeastern hole.

We furthermore emphasize the hole in the north of the disk. This asymmetric structure lines up with asymmetric structures seen before in the mid-infrared and sub-mm wavelength ranges. A possible and intriguing explanation would be a forming or existing planet, another one would be strong grain growth due to a vortex instability. Future observations will be required to answer the question of the nature of this asymmetry.

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. We thank the staff at VLT for their excellent support during the observations and F. Meru for useful discussions. This work is supported by the Swiss National Science Foundation. Facilities: VLT:Yepun (NACO)

REFERENCES

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08. 1


We estimate that the accuracy with which we can estimate the stellar position is \( \sim \) PSF halo. Values above the sensor linearity limit (10000 counts) are not taken into account for this fitting procedure.

Then, the image peaks are determined by fitting a 2-dimensional gaussian function to the stellar region around them. This procedure does not cause any problems.

We try to address all these possible effects by estimating them from the data. The fundamental assumption we make is that the errors are independent of each other. Unfortunately, the NACO detector shows a time-variable noise phenomenon across the detector rows, which cannot be eliminated by the darkframing process. Because of this, we employ a row mean subtraction, where we calculate the mean in each row of each of the four 512x512 read-out electronics of the NACO detector (mapping out the instrumental noise). In place. Unfortunately, the NACO detector shows a time-variable noise phenomenon across the detector rows, which cannot be eliminated by the darkframing process. Because of this, we employ a row mean subtraction, where we calculate the mean in each row of each of the four 512x512 read-out electronics of the NACO detector (mapping out the instrumental noise).

To avoid ghosts, we try to put the star in a region that is not close to the horizontal center of the detector, so that the (weak) ghosts lie outside the region of interest and do not cause any problems.

The ordinary and extraordinary beams are crudely extracted by finding the emission maxima and extracting the darkframes of the appropriate exposure time and flatfields of the corresponding band, with all optical elements used for the observations in place. Unfortunately, the NACO detector shows a time-variable noise phenomenon across the detector rows, which can not be eliminated by the darkframing process. Because of this, we employ a row mean subtraction, where we calculate the mean in each row of each of the four 512x512 read-out electronics of the NACO detector (mapping out the star and the more noise-affected sensor boundaries) and subtract it from the entire row. Note that this also eliminates any sky background (which is in any case very low because of the short integration times and would also be eliminated in the PDI subtraction process, given it is unpolarized). After applying this process, the resulting images show only a weak residual readout noise pattern.

From the darkframes and flatfields, bad pixel maps are constructed by mapping bad pixels (hot, dead or randomly varying). The value at the bad pixel is then replaced by the average of its surrounding pixels. The result is a clean, darkframed and flatfielded image which still contains the images of the ordinary and extraordinary beam.

We do not apply special care for ghosts in the images. These are usually unpolarized and cancel out in the PDI reduction process. We also tried to avoid having the ghosts lie on top of the ordinary or extraordinary beam in our observation plan by not putting the star close to the horizontal center of the detector, so that the (weak) ghosts lie outside the region of interest and do not cause any problems.

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INSTRUMENTAL POLARIZATION CORRECTION

The NACO instrument was not designed primarily with the focus on polarimetric observations. There are several inclined surfaces within the instrument which generate instrumental polarization, as described by Witzel et al. (2010). Because of this, we need to correct for instrumental polarization if we want to achieve the best possible signal-to-noise ratio and inner working angle for our observations. There are several instrumental effects that can occur and have to be taken into account. First, the ordinary and extraordinary beam have different transition efficiencies due to polarization effects in the light path in front of the Wollaston prism. Second, the rotation of the half-wave plate could be not perfectly aligned or instrumental polarization could slightly rotate the polarization direction. Third, the actual Stokes vectors (I, Q, U, V) suffer from polarization crosstalk, as shown by Witzel et al. (2010).

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make is that the central star is unpolarized. However, even if this was not the case and the star was polarized either intrinsically or from interstellar polarization, our data reduction would still extract the scattered light from the disk, although to a lesser degree of accuracy. Only if the star was intrinsically polarized at a level which is significant compared to the polarization efficiency of the grains (usually $>10\%$), the extraction of the disk scattered light would break down, while interstellar polarization would affect both the star and the light scattered off its disk and would be removed by our calibration process. We do not expect our target stars to be highly polarized.

In order to correct for the first-order instrumental polarization, we impose that the flux in the ordinary and extraordinary beam should be the same. Unfortunately, we cannot measure the flux of the star directly, because the central pixels in our $H$ and $K_s$ band images are saturated at the core of the PSF. However, we know that also the halo of the star should be unpolarized. The stellar halo close to the star is much too strong than the scattered light from the disk. Furthermore, for an axisymmetric disk seen face-on, the integrated light in an annulus around the star should be unpolarized as well. Because of this, we choose to calculate the ratio $X_{o/e} = f_{o/e}$ of the ordinary to extraordinary flux in an annulus between $R_{in}$ and $R_{out}$. We then multiply the image of the extraordinary beam by $(X_{o/e})^{\frac{1}{2}}$ and the ordinary beam by $(X_{o/e})^{-\frac{1}{2}}$ to equalize the flux, thus imposing a $0\%$ polarization for the stellar halo.

This improves the quality of the data significantly (see Fig. 8 b)), but further instrumental polarization effects remain. Especially, there is crosstalk between the Stokes vectors. In all the disks we analyzed, the Stokes $Q$ vector is stronger (more flux) than the Stokes $U$ vector. In a symmetric disk, this is not expected, and from the analysis of all the disks we observe, we conclude that it is an instrumental effect which we then try to quantify and calibrate. Because it is not necessarily the case that the total flux in the Stokes $Q$ and $U$ vectors is the same for a non-symmetric disk, we need a method to calculate the suppression of flux in the Stokes $U$ vector (i.e. crosstalk to circular polarization, see Witzel et al. [2010]) other than a simple ratio of the $Q/U$ fluxes. We estimate the efficiency of the measurement of Stokes $U$, denoted $\epsilon_U$, in a self-consistent way from the data. Assuming that the polarization direction in the disk is tangential (centrally symmetric) and that noise can be neglected, we expect the number of pixels in an annulus around the star, if there is a disk, in which $|Q| > |U|$, to be equal to the number of pixels where $|U| > |Q|$. We thus take an annulus where the disk is clearly detected (high SNR) and calculate $\epsilon_U$ such that $\sum I_{|Q| > |U|/\epsilon_U} = \sum I_{|U|/\epsilon_U} > |Q|$ for the sum over all the pixels in this annulus. This estimate is unbiased, although it is subject to noise, but the noise in this estimate is insignificant for our disks (the other noise sources are much stronger). We then multiply our Stokes $U$ measurement by $\frac{1}{\epsilon_U}$ in order to compensate for the fact that the efficiency of the Stokes $U$ measurement is smaller than the efficiency for Stokes $Q$. Note that this effectively means that we assume the efficiency for Stokes $Q$ to be $1$.

In the same step, we calculate the offset angle $\theta$ from equation [4]. For this, we calculate the tangential polarization $P_\parallel$ as described in equations [2] through [4], choosing $\theta$ such that $\sum P_\parallel = 0$, i.e. the average of $P_\parallel$ over all pixels in our chosen annulus is zero. This corrects for any artificial rotation of the polarization direction introduced by either misalignments of the retarder plate or crosstalk between the Stokes vectors.

As described, we calculate the tangential and radial polarization vectors $P_\perp$ and $P_\parallel$ from the data. $P_\parallel$ is expected to be zero in the absence of noise, and to not show any clear structure. In Figure 8 we summarize the effects of our instrumental polarization correction for the example of HD142527 in the $K_s$ band. As can be seen, the steps of our instrumental polarization correction significantly reduce the structure seen in $P_\parallel$. They also reduce the amount of noise in the inner part of the disk in the $P_\perp$ image (not shown here). Because of this, we conclude that the instrumental polarization correction helps suppress instrumental effects and increase the quality of the measurement of the polarized light ($P_\parallel$ image).

The reduction parameters for HD142527, HD169142 and SAO206462 can be found in Table 1. We show the inner and outer radius adopted for the equalization of the ordinary and extraordinary beam as well as the derived efficiency of the Stokes $U$ measurement and the value of $\theta$. 

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**Fig. 8.** Ur image before and after applying instrumental polarization correction. a) Ur image with no instrumental corrections at all. Strong residuals are seen, both in the disk and from the adaptive optics spots. b) After equalizing the ordinary and extraordinary beams. The adaptive optics spots are essentially gone, but there clearly is structure left where the disk is. c) After also applying the correction for $U$ and the rotation correction. Most of the structure is gone, only faint residuals remain. All images are scaled in the same way, with zero mapped to median gray.
polarization are calculated as (also described above):
\[ Q = \left( \frac{I^\parallel - I^\perp}{I^\parallel + I^\perp} \right) \]

The Stokes \( Q \) and \( U \) vectors, leading to two separate datasets for the \( H \) band.

<table>
<thead>
<tr>
<th>Target</th>
<th>Band</th>
<th>( R_{\text{in}} )</th>
<th>( R_{\text{out}} )</th>
<th>( \epsilon_U )</th>
<th>theta</th>
<th>Reference(s)</th>
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<td>HD142527</td>
<td></td>
<td>0.1''</td>
<td>0.4''</td>
<td>0.631</td>
<td>−3.7°</td>
<td>this paper</td>
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<tr>
<td></td>
<td></td>
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<td>0.4''</td>
<td>0.615</td>
<td>−3.7°</td>
<td></td>
</tr>
<tr>
<td>SAO 206462</td>
<td></td>
<td>0.15''</td>
<td>0.35''</td>
<td>0.614</td>
<td>−3.7°</td>
<td>Garufi et al. 2013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.15''</td>
<td>0.35''</td>
<td>0.645</td>
<td>−3.7°</td>
<td></td>
</tr>
<tr>
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<td>0.25''</td>
<td>0.718</td>
<td>−7.0°</td>
<td>Quanz et al. 2013</td>
</tr>
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<td></td>
<td>0.3'' (2006)</td>
<td>0.8'' (2006)</td>
<td>0.563</td>
<td>−6.6°</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3'' (2006)</td>
<td>0.8'' (2006)</td>
<td>0.561</td>
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<tr>
<td></td>
<td></td>
<td>0.3'' (2013)</td>
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<td>0.550</td>
<td>−4.6°</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3'' (2013)</td>
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<td>Avenhaus et al. in prep.</td>
</tr>
<tr>
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<td>0.8'' (2013, cube mode)</td>
<td>0.632</td>
<td>−3.9°</td>
<td></td>
</tr>
</tbody>
</table>

(a) The derotator was rotated during the observations by \( 45° \) in order to test the behavior of the Stokes \( Q \) and \( U \) vectors, leading to two separate datasets for the \( H \) band.

(b) The noise in the \( L \) band did not allow to calculate \( \theta \), thus it was assumed to be zero.

SENSOR LINEARITY MAPPING

Because we saturate the core of the point spread function (PSF), we can not use the innermost region. The NACO detector responds linearly only up to ~10,000 detector counts. We mark pixels that are in the non-linear regime of the detector as a first step, before we perform the instrumental polarization correction. Because the images are scaled and centered, the individual pixels in the final image can have contributions from both linear and non-linear pixels. In order to achieve the best possible inner working angle while still preventing our data from becoming unusable because of sensor non-linearity effects, we adopt the following scheme: We track for each individual pixel how much it is influenced by non-linear pixels. If the influence on the total value is higher than 10%, we mark this pixel as unreliable and do not incorporate it in the calculation of the Stokes parameters. This means that close to the inner working angle, some pixels in the final image may be calculated from only a subset of the individual sets of four images (for the four HWP rotations) each. While this does decrease the signal-to-noise level, we consider it to be better than having no data at all.

CALCULATION OF STOKES PARAMETERS AND STACKING

Because of being more robust and unbiased, we use the double ratio rather than the difference method to calculate the Stokes parameters \( Q \) and \( U \) (Tinbergen 2005). This means that we derive \( Q \) and \( U \) as:

\[ p_q = \frac{R_Q - 1}{R_Q + 1} ; \quad p_u = \frac{R_U - 1}{R_U + 1} \]

with

\[ R_Q = \sqrt{\frac{I_0^\parallel}{I_{\text{extra}}^\parallel} \frac{I_0^\perp}{I_{\text{extra}}^\perp}} ; \quad R_U = \sqrt{\frac{I_{22.5\degree}^\parallel}{I_{\text{extra}}^\parallel} \frac{I_{22.5\degree}^\perp}{I_{\text{extra}}^\perp}} \]

Here, the subscripts refer to either the ordinary or extraordinary beam and the superscripts refer to the angular position of the HWP. The Stokes \( Q \) and \( U \) parameters are then simply calculated as

\[ Q = p_q * I_Q ; \quad U = p_u * I_U \]

where

\[ I_Q = \left( I_{\text{ord}}^\parallel + I_{\text{extra}}^\parallel + I_{\text{ord}}^{45\degree} + I_{\text{extra}}^{45\degree} \right) / 2 ; \quad I_U = \left( I_{\text{ord}}^{22.5\degree} + I_{\text{extra}}^{22.5\degree} + I_{\text{ord}}^{67.5\degree} + I_{\text{extra}}^{67.5\degree} \right) / 2 \]

are the total intensities in the images used for the calculation of \( p_q \) and \( p_U \). Finally, the radial and tangential polarization are calculated as (also described above):

\[ P_\perp = +Q \cos 2\phi + U \sin 2\phi ; \quad P_\parallel = -Q \sin 2\phi + U \cos 2\phi ; \quad \phi = \arctan \frac{x - x_0}{y - y_0} + \theta \]

This is done for each quadruplet of images (four images for four HWP position angles). All individual Stokes \( Q \), \( U \), \( P_\perp \), \( P_\parallel \) and \( I \) measurements are then mean-combined (ignoring those pixels that have been identified as being in the
Structures in the protoplanetary disk of HD142527 seen in polarized scattered light in the non-linear detector regime) to yield the final results.