Subaru/HiCIAO HK_s Imaging of LKHa 330: Multi-band Detection of the Gap and Spiral-like Structures

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Abstract

We present H - and K_s -bands observations of the LkHa 330 disk with a multi-band detection of the large gap and spiral-like structures. The morphology of the outer disk ($r \sim 0.3$) at $PA = 0^\circ$ – 45° and $PA = 180^\circ$ – 290° is likely density wave-induced spirals, and comparison between our observational results and simulations suggests a planet formation. We have also investigated the azimuthal profiles at the ring and the outer-disk regions as well as radial profiles in the directions of the spiral-like structures and semimajor axis. Azimuthal analysis shows a large variety in wavelength and implies that the disk has non-axisymmetric dust distributions. The radial profiles in the major-axis direction ($PA = 271^\circ$) suggest that the outer region ($r \geq 0.25$) may be influenced by shadows of the inner region of the disk. The spiral-like directions ($PA = 10^\circ$ and 230°) show different radial profiles, which suggests that the surfaces of the spiral-like structures are highly flared and/or have different dust properties. Finally, a color map of the disk shows a lack of an outer eastern region in the H -band disk, which may hint at the presence of an inner object that casts a directional shadow onto the disk.

Key words: planet–disk interactions – polarization – protoplanetary disks

1. Introduction

A protoplanetary disk loses almost all of its mass after a few million years (Haisch et al. 2001; Currie et al. 2009; Cloutier et al. 2014; Ribas et al. 2015), during which the disk can be perturbed by accretion, jets, photoevaporation, dust growth, and planet formation (e.g., Crida & Morbidelli 2007; Armitage 2011). Previous theoretical simulations predicted gaps within disks, which is likely related to planet formation (e.g., Marsh & Mahoney 1992; Rice et al. 2003; Zhu et al. 2011, 2012). In recent years, dozens of high spatial resolution observations have revealed a diversity of shapes within disks such as gaps, rings, and spiral features (e.g., Hashimoto et al. 2011; Muto et al. 2012; ALMA Partnership et al. 2015; Pérez et al. 2016). Radio observations allow investigation of the gas and dust distributions of disk and infrared (IR) observations provide scattered light information from the surface of disks. Particularly, possible planet-disk interactions for many of these disk shapes have been suggested (Zhu et al. 2015; Dong & Fung 2017), as well as other predictions such as dust sintering (Okuzumi et al. 2016). However, the number of reported companion candidates within the disks is much smaller than the number of asymmetric disks (Quanz et al. 2013; Reggiani et al. 2014, 2017; Currie et al. 2015; Sallum et al. 2015). Therefore continuing explorations of disk and companions is important for the study of planet formation and disk evolution mechanisms.

A class of disks having an inner cavity, called transitional disks, is of particular interest in studying the disk evolution and dissipation. Some of the transitional disks are expected to harbor a small inner disk that is optically thick in optical/near-IR around a central star and are called pre-transitional disks (Espaillat et al. 2010, 2014). In this paper, we report the result of near-infrared scattered light imaging observations of LkH α 330. LkH α 330 is a young stellar object (YSO) in the Perseus association ((R.A., decl.) = (03 45 48.28, +32 24 11.9)). This system exhibits the spectral feature of a pre-transitional disk (Espaillat et al. 2014) and Brown et al. (2007) suggested an inner disk by showing polycyclic aromatic hydrocarbon features. Furthermore, mm and sub-mm observations have reported that the disk has a large ($\sim 0''.16$ – $0''.27$) gap (Brown et al. 2008; Andrews et al. 2011; Isella et al. 2013) and IR observations have suggested spirals (Akiyama et al. 2016). These studies suggest grain growth and possibly unseen planets within the disk that may cause the large gap and spirals. To follow-up the earlier studies on this intriguing system we conducted H - and K_s -bands observations of LkH α 330 as a part of the Strategic Explorations of Exoplanets and Disks with Subaru (SEEDS; Tamura 2009) project.

In this paper, we describe our observations and data reduction in Section 2 and present our results and data analyses are shown in Section 3. In Section 4, we discuss the detected features in the disk and summarize our results.

2. Observations and Data Reduction

The observations and data for LkH α 330, which are analyzed in this study, have been reported previously in Uyama et al. (2017).

We made H -band ($\sim 1.6 \mu\text{m}$) observations of LkH α 330 in 2014 October and K_s -band ($\sim 2.2 \mu\text{m}$) observations in 2015 January with Subaru/HiCIAO (Suzuki et al. 2010a) combined with classical AO system AO 188 (Hayano et al. 2008). A

typical FWHM of each unsaturated point-spread function (PSF) is ~ 80 mas in the H -band and ~ 70 mas in the K_s -band. The data of this study were obtained without a coronagraph for both the H - and K_s -band observations. Note that Akiyama et al. (2016) also used Subaru/HiCIAO to observe this system in 2011 December but adopted a $0''.4$ coronagraph mask, which prevents exploration of the gap region of the disk. The data sets were taken by combining polarization differential imaging (PDI) to investigate faint disk structures and angular differential imaging (ADI) to detect substellar companions around the central star. Detailed observation logs are shown in the SEEDS/YSO comprehensive report of Uyama et al. (2017), which applied only ADI reduction (Marois et al. 2006; Lafreniere et al. 2007) for companion explorations. This study focuses on the data analysis of PDI. We used the “quad-PDI” (qPDI) mode where two Wollaston prisms enable the acquisition of two ordinary and extraordinary rays on one frame simultaneously. Each field of view is $\sim 5'' \times \sim 5''$ and the plate scale after distortion correction is 9.5 mas/pix. After the first reduction of flat fielding, distortion correction, and image registration, all the polarimetric data sets were reduced in the same way as Hashimoto et al. (2011, 2012) using IRAF.

3. Results and Data Analysis

3.1. Basic Parameters of LkH α 330

LkH α 330 was assumed to have 250 pc for a distance, 3 Myr old for an age, and GIII for a spectral type (Cohen & Kuhi 1979; Enoch et al. 2006) in the previous studies introduced in Section 1. However, *Gaia* DR2 recently reported the distance to be 311 ± 8 pc (Gaia Collaboration et al. 2016, 2018). Therefore, we adopt the GAIA-measured distance in our discussion. Herczeg & Hillenbrand (2014) estimated a spectral type of LkH α 330 to be F7.0 by analyzing its optical spectra with an assumed distance of 315 pc. We converted the spectral type of F7.0 to the effective temperature using the relationship between a spectral type and effective temperature in Pecaut & Mamajek (2013). We used B- and V-band magnitudes (Mermilliod 1987) to determine extinction-corrected V-band magnitude, which was converted to a LkH α 330’s bolometric luminosity based on Pecaut & Mamajek (2013). These effective temperature and luminosity described above were compared to the Pisa pre-main sequence evolution tracks (Tognelli et al. 2011). Finally, we estimate a mass and age of LkH α 330 to be $2.8 \pm 0.2 M_\odot$ and 2.5 ± 0.7 Myr, respectively.

3.2. Polarized Intensity Image

We detected a large gap and spiral-like features with signal-to-noise ratios (S/N) of >30 at the peak of the ring and >20 at the peak of the spiral regions. Figure 1 shows H and K_s r^2 -scaled polarization intensity (PI) images. The PI parameter is dependent on r^{-2} and we scaled this parameter by multiplying PI image by r^2 so that we can more properly see the structures. We note that this treatment corresponds to neglecting the disk flaring when calculating scattering angle, and may be problematic when discussing the disk structures quantitatively (Stolker et al. 2016). In this paper, we present some characteristic features on radial and azimuthal profiles and disk asymmetry of the disk, but keep the discussions on them at more or less qualitative levels. The contours taken from the Submillimeter Array (SMA) observation ($\lambda = 0.87$ mm)

Figure 1. Subaru/HiCIAO r^2 -scaled PI image of LkH α 330 in the H - (left) and K_s -bands (right). The scale bar is arbitrary. The SMA ($\lambda = 0.87$ mm) observation result is overlaid on both images as gray contours. The levels are the same as those shown in Akiyama et al. (2016). Perpendicular blue lines in the K_s image represent semimajor and semiminor axes. North is up and east is left.

Figure 2. H and K_s Polarization vector maps superimposed on the PI maps.

discussed in Akiyama et al. (2016) are superimposed on the figures.

To estimate the S/N ratio, we first measured the polarization vector as seen in Figure 2 and defined θ_{err} as the difference of the angle between the polarization vector and the vector normal to the position vector measured from the central star. We then calculated radial profiles (see Figure 3) and converted the polarization angle error into a polarization error using an Equation (6) in Kwon et al. (2016). In this estimate of the error, we assume that the “real” polarization vectors are centro-symmetric around the central star. The observed polarization pattern is indeed very close to centro-symmetric (see Figure 2) and the non-azimuthal polarization such as T Cha (Pohl et al. 2017) is probably negligible. We define noise as the standard deviation at given annular areas like ADI contrast limit (see Section 3.7 and Uyama et al. 2017).

3.3. Gap Region

We traced the inner wall (hereafter we call this the “ring”) region in the r^2 -scaled PI images and then fitted the peak profiles with an elliptic equation $\left(\frac{x-x_{\text{cen}}}{a}\right)^2 + \left(\frac{y-y_{\text{cen}}}{b}\right)^2 = 1$, in

Figure 3. Polarization position angle errors as a radial profile in each image.

which a and b are the semimajor axis and semiminor axis. Table 1 compares the cavity radius, position angle of the semimajor axis, and inclination from previous studies and this work. In the calculation we used the nonlinear least-squares (NLLS) Marquardt–Levenberg algorithm implemented into gnuplot. The error bars represent 1σ asymptotic standard

Table 1
Adopted Parameters of the Disk

Parameters	Previous study	This study
semimajor axis [au] ^a	50 ^b –84 ^c	54 ± 1
position angle [degree]	80 ^b	91 ± 2
inclination [degree]	35 ^b	31 ± 3

Notes.

^a Angular separations do not change, and thus we scaled the size reported from previous studies by the distance of 310 pc.

^b Brown et al. (2008).

^c Andrews et al. (2011).

error. We note that previous studies used the midplane of the disk for measuring the gap while we used the surface brightness of the disk. Observations of transitional disks have systematically revealed bigger cavity sizes in the mm continuum than in scattered light (Dong et al. 2012), e.g., PDS 70 (Hashimoto et al. 2012, 2015) and 2MASS J1604 (Mayama et al. 2012; Dong et al. 2017). This phenomenon may be explained as being due to mm-sized dust being filtered out at the cavity edge due to gas-dust coupling effect (e.g., Rice et al. 2006; Zhu et al. 2012; Dong et al. 2015b). Here we report that LkH α 330 is another example of this class of object. Andrews et al. (2011) modeled mm continuum emission of the disk and concluded that the cavity size is 84 au (0".27; see also Isella et al. 2013). The NIR cavity size seen by Subaru is only $\sim$ 54 au, much smaller than the mm cavity size.

3.4. Spiral-like Region

As discussed in Akiyama et al. (2016) the two peaks of the SMA continuum are located at spiral-like features. Interestingly, the surface and midplane distributions at the south–west region are consistent, while the north–east region does not exhibit a similar distribution. Figure 4 shows deprojected and r^2 -scaled PI images and Figures 5 and 6 show polar-projected images taken from Figure 4. We traced the ridge of the spiral-like structures, which is superimposed on the images (blue crosses). The morphology of the outer region implies that the disk’s rotation is counter-clockwise. Note that we did not change the scattering angle when deprojecting the PI images but changed their inclinations to zero only for the purpose of tracing the peaks of the outer structures.

We can now see clear deviations from the axisymmetric ring-like structure at $r \sim 200$ mas. There are two spiral structures: one is launched at about PA = 290° and the other is at PA = 70°. We find that the H - and K_s -band observations have different shapes of the outer asymmetric features. For the south–west non-axisymmetric features, they extend from PA $\sim$ 290° to 180° both in H - and K_s -bands, and they appear like “spiral” features. For the north–east feature, however, the H -band feature extends from PA $\sim$ 70° to 0° and it does appear like a “spiral,” while in the K_s -band, the emission between PA $\sim$ 40° and 0° is missing. The appearance of the north–east feature in the K_s -band may be described as “slightly inclined blob.” Anyway, the inclined spirals can have complex morphology (e.g., Dong et al. 2016a) and we discuss the possibility of the spiral in Section 4.1.2.

We could trace the peaks of the south–west structure between PA = 180°–270° in the H -band and between PA = 180°–290° in the K_s -band. On the other hand, we could

trace the peaks of the north–east structure between PA = 0°–70° in the H -band and between PA = 40°–60° in the K_s -band. We investigated angles between the roots of the spirals and the ring by using the H -band result for north–east structure and the K_s -band result for south–west structure. The pitch angles are determined to be $\sim$ 12° and $\sim$ 16° for the south–west and north–east structures, respectively. These values are similar to the SAO 206462 spirals (Muto et al. 2012).

However, we note a weak tendency from the “spiral top” toward the other side of disk in Figures 5 and 6, which possibly represents another mechanism. A trailing spiral behaves as a monotonically increasing profile (Goldreich & Tremaine 1979). The spiral density wave is likely to be a trailing feature, and it may be difficult to explain the blob-like morphology that we see in the north–east in the K_s -band image. Since previous SMA and CARMA observations did not report any specific features except for the central large gap, identifying these asymmetric outer structures requires follow-up observations with a high spatial resolution.

3.5. Azimuthal Profiles

3.5.1. Ring Region

We investigated the surface brightness profiles of the deprojected image after averaging over 5×5 pix so that we can expect to reduce the noise at the pixel scale. Figure 7 shows azimuthal profiles of the deprojected PI images at separations of $r = 0''.17$ and $0''.25$. We find that azimuthal profiles at the ring region ($r = 0''.17$) show strong wavelength dependence. This is in contrast to the results of multi-band observations of the disk in other systems (e.g., Benisty et al. 2017). The south direction (PA $\sim$ 180°) is the brightest in the H -band profile. Considering that the minor axis of the disk is in the north–south direction (see Section 3.3), this is probably due to the excess of forward scattering and therefore the southern side of the disk is likely to be the near side. However, in the K_s -band, the scattered light is the brightest in the eastern side, which is along the major axis of the disk. Such a large variation in the scattered light profiles in different bands might suggest that the dust distribution is not azimuthally symmetric. This issue will be further discussed in Section 4.2.1.

3.5.2. Outer Region

Our H -band profile at $r = 0''.25$ is different from Akiyama et al. (2016), particularly at the north region. The previous observation used the coronagraph mask and did not explore the central region, while our observation could explore much inner region. Our profile might be partially influenced by the asymmetric dust distribution of the ring. We also find that these profiles are quite different from the ring azimuthal profile, particularly the relative decline of the surface brightness at the forward scattering region. The spiral-like features appear at $r \sim 0''.3$ in Figures 5 and 6, but our data sets suggest that the $r \sim 0''.25$ area likely belongs to the outer spiral-like region.

3.6. Radial Profiles

Figure 8 shows radial profiles between $0''.15$ and $0''.45$ in both the H - and K_s -band PI images. These profiles have azimuthal asymmetry. The PAs 10° and 230° correspond to both spiral-like features. 91° and 271° correspond to the semimajor axis directions. We used the least-squares method

Figure 4. Deprojected and r^2 -scaled H - (left) and K_s -band (right) PI images. We additionally plot traced peaks of the spiral-like structures using blue crosses. Note that we have changed the scale bars from those in Figure 1 in order to make the outer structures clearer.

Figure 5. Polar-projected H -band PI image after deprojection and scaling by squared separations of r^2 . The color scale is arbitrary. In order to make it easier to find outer asymmetric features, we started PA from -45° .

Figure 6. As Figure 5 for the K_s -band.

on these profiles and a power law to investigate the surface structure of the disk. The fitted powers are listed in Table 2. Except at the ring and spiral-like regions, the surface brightness is in proportion to the separation, to the power of no larger than two, and is different from a flared disk’s behavior. An r^{-3} profile can be explained with a flat disk (Momose et al. 2015), which can produce shadows due to surface structures and make the surface brightness profiles complex.

Within $r < 0''.26$ the H and K_s profiles are similar but have small difference. This difference may reflect a difference in the ring’s scattering between the H - and K_s -bands. In both bands, the inner regions (H : ≤ 40 au, K : ≤ 45 au) behaves as highly flared disks, which creates shadows outward (H : 50–75 au, K : 55–80 au). By combining these features, we can assume that the K_s -band ring extends more than the H -band ring.

At the outer region the fitted powers are smaller than -2 along $PA = 271^\circ$ direction, which suggests that the disk’s surface in the semimajor axis directions also behaves as a flat

disk influenced by shadows. $PA = 91^\circ$ profile is the semimajor axis direction but mixed with the spiral-like structure. In $PA = 10^\circ$ and 230° directions the profiles exhibit a more gradual change, with a steep decrease at separations greater than $r > 0''.4$. These profiles are consistent with flaring of the spiral-like structure and these region may have different dust properties.

3.7. Angular Differential Imaging

As companion exploration, Uyama et al. (2017) conducted an ADI reduction of all the LkH α 330 data sets and could not find any companion candidates around the central star. Figure 9 shows our ADI-reduced image of the K_s -band observation. We performed ADI-LOCI reduction (Lafreniere et al. 2007) and the algorithm automatically masked a $\sim 0''.15$ region from the center. Our ADI-LOCI pipeline did not work properly for the nearly face-on disk, resulting in artificial residual pattern as seen in Figure 9. Therefore, one cannot discuss the morphology of the disk in the ADI-LOCI reduced image. Nonetheless, the image can be used to constrain the flux from a possible point-like source. Some signals remain around the central star but their S/N ratios are less than five, and therefore we regard them as being residual from the PSF subtraction.

The contrast limits have already been described in Uyama et al. (2017), and were converted into mass limits based on the COND03 model (Baraffe et al. 2003). Figure 10 shows the mass limit of our observations. We have set constraints on the mass of potential companions in the disk down to $\sim 20 M_J$. The shadows correspond to errors of our age estimation. The conversion was based on the “hot-start” model (BT-Settl; Allard et al. 2011).

Besides age, planet mass limits could also be uncertain due to assumed planet luminosity evolution models. “Hot-start” evolutionary models such as those we adopt are often associated with disk instability formation. “Cold-start” models (Marley et al. 2007) attempt to model planet formation by core accretion and yield lower initial entropies and luminosities and thus higher masses for a given contrast limit (though see Berardo et al. 2017). However, demographics suggest that companions with these masses/mass ratios and separations detectable from our data are likely not planets formed by core accretion (Currie et al. 2011; Brandt et al. 2014). Thus, our

Figure 7. Azimuthal surface brightness profiles at $\sim 0''.17$ (left) and $\sim 0''.25$ (right).

mass limits are likely to probe only companions formed like binary stars or by disk instability.

4. Discussions

The disk around the LkH α 330 has complex morphology. In this section, we focus on disk features one by one and discuss the implications on the disk properties, which will help to synthetically model the disk and to investigate disk evolution mechanisms such as gap opening and spiral forming with unseen planets.

4.1. Morphology

4.1.1. Gap

Previous observations of LkH α 330 suggested planet formation within the gap (e.g., Zhu et al. 2012; Isella et al. 2013). Our ADI reduction could not fully explore the gap region and thus planet formation remains a plausible but unconfirmed scenario.

Grain growth (e.g., Birnstiel et al. 2012) and disk wind (e.g., Suzuki et al. 2010b) are also possible mechanisms for opening the gap in the disk. A spectral feature of LkH α 330 is an excess at the mm and sub-mm wavelength ranges (Brown et al. 2008; T. Hitchcock 2018, in preparation), which suggests the existence of larger dust and supports the possibility of grain growth. Investigating disk wind will require follow-up observations of gas kinematics; the presence of disk wind is suggested if blueshift components excel in the data. Although photoevaporation can produce a gap within the disk (e.g., Clarke et al. 2001; Goto et al. 2006; Owen et al. 2011), the disk mass is much larger ($M_{\text{disk}} \sim 0.01 M_{\star} \geq 0.02 M_{\odot}$; Andrews et al. 2011) than expected mass of the photoevaporation stage (an order of $0.001 M_{\odot}$; Alexander et al. 2006).

4.1.2. Spiral-like Structures

The LkH α 330 system may be another disk, after SAO 206462 (Muto et al. 2012), MWC 758 (Grady et al. 2013), HD 100453 (Wagner et al. 2015), DZ Cha (Canovas et al. 2018)

(note that the inner disk in the AB Aur system, Hashimoto et al. 2011, has also been suggested to host two spiral arms, Figure 14 in Dong et al. 2016a), that has been discovered to have a pair of nearly symmetric spiral arms in scattered light. Except for HD 100453, which has an M dwarf companion that is probably driving the arms (Dong et al. 2016b; Wagner et al. 2018), the origin of the spiral arms in the other systems is under debate. Two mechanisms are proposed to explain the morphology of these near $m = 2$ arms: gravitational instability (e.g., Dong et al. 2015a), and companion-disk interaction (e.g., Dong et al. 2015a; Zhu et al. 2015). As LkH α 330's disk mass is perhaps too low to trigger the gravitational instability ($M_{\text{disk}} \sim 0.01 M_{\star}$; Andrews et al. 2011), we consider companion-disk interactions to constitute a plausible scenario.

We carried out three-dimensional hydrodynamics and radiative transfer simulations to produce synthetic images of a pair of planet-induced spiral arms in scattered light that qualitatively match the Subaru observations of LkH α 330, as shown in Figure 11. The simulation was conducted based on the planetary-mass-companion model in Dong et al. (2016a), and is briefly described here. We use the hydrodynamics code PENGUIN (Fung 2015) to calculate the density structure of a disk perturbed by a planet in a circular orbit at 100 au. The resulting disk structure is translated into near-IR polarized light images using the radiative transfer code HO-CHUNK3D (Whitney et al. 2013). The planet's mass was $M_{\text{planet}} = 0.003 M_{\star}$, which corresponds to $\sim 6 M_J$ in LkH α 330. The synthetic image was produced assuming the object is 310 pc away, and under the actual viewing angle of the system, PA = 90° and inclination $i = 30^\circ$. The image was convolved by a Gaussian PSF to achieve an angular resolution of $0''.06$. The outer disk exterior to the planet's orbit was removed in post-processing. The model image matches the actual data well, which suggests that the two spiral arms in LkH α 330 may be induced by a 5–10 M_J planet at ~ 120 au ($0''.4$). At the current epoch, the planet may be at PA $\sim 20^\circ$. Note that these simulations focus on reconstructing a pair of spirals in the LkH α 330's disk and are separate from those reported in Isella et al. (2013) that predicted unseen protoplanets within the gap region.

Figure 8. Radial profiles in the H - and K_s -band data sets. The gray lines are power-law-fit results at three separations. The fitted results are shown in Table 2.

Table 2
Power-law Fit of Radial Profiles

PA [degree]	H			K_s		
	$0''.1 < r \leq 0''.15$	$0''.15 \leq r \leq 0''.24$	$0''.24 \leq r \leq 0''.40$	$0''.1 < r \leq 0''.18$	$0''.18 \leq r \leq 0''.26$	$0''.26 \leq r \leq 0''.40$
10	-0.44	-4.1	-0.65	-0.10	-5.4	-6.5×10^{-2}
91	-1.2	-5.1	-0.91	-1.2	-4.6	-0.70
230	-5.0×10^{-2}	-3.5	-1.0	7.8×10^{-3}	-4.6	-0.33
271	-6.5×10^{-2}	-2.9	-7.0	9.0×10^{-2}	-2.4	-5.2

Figure 9. ADI-reduced image in the K_s -band. North is up and the central star is masked by the algorithm.

Figure 10. Mass limits of the ADI-reduced images. The vertical axis is mass in M_J unit and the horizontal axis is the projected separation. We converted the contrast limit into mass units by the BT-Settl model assuming that possible companions can clear the gas and dust locally and that the conversion can ignore extinction from the disk.

4.2. Color Discussion

We have observed LkH α 330 in the H - and K_s -bands and can discuss a disk variation in wavelength. In this section we focus on the difference between the azimuthal profile of the ring shown in Figure 12 and a color map of the disk.

4.2.1. Scattering Properties

We investigated phase functions of a grain-scattering model in Figure 12 using Equations (8) and (9) in Graham et al. (2007), where we fixed the polarization parameter of $p_{\max}$ to 1.

We put four dotted lines in each graph by changing the scattering parameter of g and a coefficient of the phase function in order to compare the phase functions to the ring profiles. A formula of the phase function is given by

$$\propto \frac{1 - g^2}{4\pi(1 + g^2 - 2g \cos \theta \sin i)^{3/2}} \cdot p_{\max} \frac{1 - \cos^2 \theta \sin^2 i}{1 + \cos^2 \theta \sin^2 i},$$

where θ is a scattering angle and i is an inclination. Figure 13 is a polar diagram of Henyey–Greenstein phase function ($\Phi(a) = \frac{1 - g^2}{4\pi(1 + g^2 - 2g \cos(a))^{3/2}}$, where a is a phase angle; Henyey & Greenstein 1941) by changing g from 0 to 0.6, which shows the dependency of scattering angle on the phase function. Forward scattering angle is given by $\pi/2 - i - \beta$ where β is an opening angle of the disk (see Figure 9 in Jang-Condell 2017). We assume that the disk is geometrically thin and β is negligible. Our adopted phase functions partially deviate from the azimuthal profiles of the ring. These phase functions have similar profiles at the brightest region. The H -band functions with $g > 0.5$ may be more suitable for the profile at PA $\sim 90^\circ$ – 270° , while $g = 0$ fits the profile at PA $\sim 90^\circ$ in the K_s -band. However, these functions do not fully agree with the ring profiles. Apparently at the north region (PA $\sim 0^\circ$) both rings are much brighter than the expected phase functions and K_s -band azimuthal profile three peaks, which cannot be reproduced by a simple phase function we adopt and may suggest the ring has non-axisymmetric distribution of dust and/or composition.

In order to investigate whether such large variations of the scattering properties with a simple dust model, we run a Mie scattering code attached to the HO-CHUNK radiative transfer code (Bohren & Huffman 1983; Whitney et al. 2003) assuming the astronomical silicates model (Laor & Draine 1993). When we defined the dust size so as to reproduce the K_s -band $g = 0$ value by changing minimum dust size between 1 nm and 300 nm, the g value in the H -band was automatically defined and was always smaller than 0.5. This result indicates that the ring profiles cannot be described by a simple dust species distributed all over the entire disk. Our assumptions and calculations could not characterize the disk fully but might set particular constraints on the dust distribution.

Explaining these variations requires non-axisymmetric pattern of size, density, and composition distributions and vertical structures. As ALMA revealed that MWC 758 has complexity in its ring (Boehler et al. 2018; Dong et al. 2018), radio interferometric observations will help to reveal dust size and density distributions. Identifying its composition requires follow-up observations in other bands, e.g., with *JWST*/MIRI (Wells et al. 2015) or TMT/MICHI (Sakon et al. 2014). A future integral field spectroscopy (IFS) in mid-IR wavelength

Figure 11. Comparison of r^2 -scaled surface brightness of outer structures in the H -band (left), K_s -band (middle), and model (right) images. The color bars are arbitrary. We overlay an $r = 0''.2$ mask on all the images because the model calculation focuses on reproducing only the outer features.

can constrain abundance of polycyclic aromatic hydrocarbon and silicate. The wavelength difference of the azimuthal surface brightness structures shown in Figure 12 may not be simply explained by the azimuthal variations of the vertical structures and therefore investigating synthetic dust distributions will be necessary.

4.2.2. Color Map

Figure 14 shows a color map of the disk generated by dividing the K_s -band PI image by the H -band PI image. In this process the K_s -band image is convolved in order to fit the K_s -band’s PSF to the H -band’s PSF. AO188 worked effectively enough to suppress both PSF’s wings and the H -band PSF’s core is broader as mentioned in Section 2. We then re-registered two PDI-reduced images by defining the center as the elliptical-fit results of the ring. Finally we normalized the K_s/H PI image by the K_s/H luminosity of the central star ($=2.27$ from UCAC4 catalog; Zacharias et al. 2012).

We find that the disk is basically “blue.” This implies that the typical dust size is small enough for Rayleigh scattering. However, there are seen some “redder” regions at $(\rho, \text{PA}) = (\sim 0''.3, 0^\circ\text{--}30^\circ)$ and $(0''.15\text{--}0''.4, 45^\circ\text{--}90^\circ)$. The northern part ($\sim 0''.3, \sim 0^\circ\text{--}30^\circ$) is influenced by the north-east spiral-like feature that appears only in the H -band image (see Figures 4–6). The inner eastern part ($0''.15\text{--}0''.2, 45^\circ\text{--}90^\circ$) corresponds to the wavelength difference of the azimuthal profiles, which is discussed in Section 4.2.1.

The outer eastern part ($0''.2\text{--}0''.4, 45^\circ\text{--}90^\circ$) comes from the lack of an outer scattering area in the H -band disk. The H -band PI image previously reported in (Akiyama et al. 2016), which is presented as a r^2 -scaled PI image in Figure 16, looks like the K_s -band image. A comparison of the FWHMs of the previous and our H -band image shows that our data sets had better AO efficiency. Therefore, our data reduction shows a “red” region at the outer north-east region. This phenomenon demonstrates that a possibility of “a directional shadow” is plausible; namely, when we observed this system, an inner object occasionally partially veiled starlight and cast a shadow onto the north-east region of the disk. We consider a clump-like object moving in the very inner region. If the orbit of the object is highly misaligned with the outer disk, we can explain the change of outer morphology over the three months. The orbital separation is expected to be very near (≤ 1 au) the central star. Regarding the possibility of there being an inner clump, we refer to CVSO 30 and “dipper” stars. CVSO 30 was reported to harbor a close-in protoplanet candidate based on transit

observations (CVSO 30 b; van Eyken et al. 2012). However, follow-up observations suggested that the companion candidate is a clump rather than a planet (Onitsuka et al. 2017). Dipper YSOs revealed by the K2 survey suggest the existence of occulting structures located at quite small separations (Ansdell et al. 2016). Particularly, Ansdell et al. (2016) reported RX J1604.3-2130A to be a dipper star. This YSO has a face-on disk with a large gap (e.g., Mayama et al. 2012). Therefore an inner clump-like object with an orbit highly misaligned to the outer disk is a possible scenario.

Another possible mechanism of casting shadow in the outer disk is the existence of an inner disk. Previous disk observations have revealed shadows on the protoplanetary disks induced by inner objects (Garufi et al. 2014; Pinilla et al. 2015; Stolker et al. 2016, 2017; Benisty et al. 2017; Canovas et al. 2017; Debes et al. 2017). If LkH α 330 has an inner disk that can cast shadows on the outer disk, non-axisymmetric structures can be observed (Facchini et al. 2018). From the models presented in Long et al. (2017), we consider that the difference of the inclination between the inner and the outer disks is as small as $<10^\circ$ in order to produce the azimuthal features observed in H -band. Given that our K_s -band image, which was taken just three months after the H -band image; however, this rapid change of the shadow feature can hardly be explained by the change of the orientation of the inner disk because we do not expect rapid (on the timescale comparable to *Kepler* timescale) precession of the inner disk. The inner disk should have a particular extinction property to let K_s -band wavelength transmit. As multi-band observations of HD 100453 (Benisty et al. 2017) did not show clear difference of the shadow structures, we consider that the shadowing by the inner disk is unlikely.

In order to investigate this scenario, follow-up observations are required. If the PI signal is detected again as reported in Akiyama et al. (2016), a clump-like object scenario is plausible. However, if follow-up observations fail to detect a PI signal, other scenarios should be considered, such as asymmetric dust distribution or difference of dust properties between the outer and inner disks.

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Figure 12. Azimuthal surface brightness profiles of the deprojected ring region ($r \sim 0''.17$) in the H -band(left) and K_s -band (right). We include expected phase functions assuming a uniform dust distribution in the disk.

Figure 13. Polar diagram of Henyey–Greenstein phase function. The phase angle corresponds to a deviation from the forward-scattering direction. The radial scale is arbitrary.

Figure 14. Color map of the LkH α 330 disk. The scale bar represents the PI ratios K_s/H such that red represents a larger value.

Observatories of Japan. Based in part on data collected at Subaru telescope and obtained from the SMOKA, which is operated by the Astronomy Data Center, National Astronomical Observatory of Japan. Data analysis were carried out on common use data analysis computer system at the Astronomy Data Center, ADC, of the National Astronomical Observatory of Japan. This research has made use of NASA’s Astrophysics Data System Bibliographic Services. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This research has made use of the VizieR catalog access tool, CDS, Strasbourg, France. The original description of the VizieR service was published in A&AS 143, 23.

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Appendix A Error Map of Polarization Angle

Figure 15, which is made from Figure 2, shows angle error maps in the H - and K_s -bands. These maps are used for calculating noise profiles of the PI images and details are explained in Section 3. Yellow corresponds to larger difference from a centro-symmetric pattern of the polarization vectors and causes larger noise in the PI image.

Appendix B Comparison of Our Results with the Previous HiCIAO Image

Figure 16 compares our HiCIAO observations with the previous HiCIAO observation that was originally presented in Akiyama et al. (2016). Our data sets achieved better AO efficiency and are explained in Section 2.

Figure 15. Angle error maps of the H - (left) and K_s -band (right) images. These maps are used for calculating radial noise of the PI images, which is described in Section 3.

Figure 16. r^2 -scaled PI images in the H -band taken in 2014 (left), the K_s -band taken in 2015 (center), and the H -band taken in 2011 (right). The right image is masked with a $0.2''$ -radius mask.

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