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NEAR-INFRARED IMAGING POLARIMETRY OF LkCa 15: A POSSIBLE WARPED INNER DISK[†]

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Abstract

We present high-contrast H-band polarized intensity images of the transitional disk around the young solar-like star LkCa 15. By utilizing Subaru/HiCIAO for polarimetric differential imaging, both the angular resolution and the inner working angle reach 0.07″and r=0.1″, respectively. We obtained a clearly resolved gap (width $\lesssim$ 27 AU) at $\sim$ 48 AU from the central star. This gap is consistent with images reported in previous studies. We also confirmed the existence of a bright inner disk with a misaligned position angle of 13$\pm$4° with respect to that of the outer disk, i.e., the inner disk is possibly warped. The large gap and the warped inner disk both point to the existence of a multiple planetary system with a mass of $\lesssim$1$M_{\rm Jup}$.

Key words: circumstellar material — stars: individual (LkCa 15) — stars: pre-main-sequence — planetary systems: protoplanetary disks

1 Introduction

The circumstellar disks around young stars are the main birthplace of giant gas planets. Analysis of their spectral energy distribution (SED) and the results of interferometry at infrared to millimeter wavelengths reveal the evidence of gap and cavity structures in many circumstellar disks. Such disks have been called transitional disks, and are thought to be an intermediate phase between gas-rich primordial disks and gas-poor debris disks (e.g., Espaillat et al. 2014). When newly formed planet(s) are embedded in the disks, a gap structure (i.e., optically thick inner and outer disks separated by an optically thin gap) instead of a cavity (i.e., a complete lack of an inner disk) is predicted to form by disk-planet interactions (Kley & Nelson 2012). Therefore, disks with a gap structure could indicate the birth of the giant gas planets. Hence, understanding the detailed structures of the transitional disks could unveil the origin of our planetary system.

The progress of high-contrast imaging in the last decade allows us to see more details in the transitional disks. By direct imaging, the incredible diversity of the disk morphology, such as spiral and gap structures, has been revealed (e.g., Hashimoto et al. 2012). LkCa 15 (K5, 0.97 $M_\odot$, 2$-$5 Myr old; Simon et

[†] Based on IRCS and HiCIAO data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

al. 2000), a young solar-like star located in the Taurus-Auriga region (∼140 pc), is one of the most intensively studied transitional disk systems around the T Tauri star. Espaillat et al. (2007) conducted a detailed analysis of SED in LkCa 15 and suggested the existence of a gap structure at ∼46AU. Such a gap structure has been confirmed by millimeter (mm) interferometry (Piétu et al. 2006) and near-infrared (NIR) high-contrast direct imaging (Thalmann et al. 2010).

Subsequently, protoplanet candidates LkCa 15 b and c ($\lesssim$5∼10$M_{\rm Jup}$) were discovered (Kraus & Ireland 2012; Sallum et al. 2015). More recently, the inner disk was newly discovered by Thalmann et al. (2015) at optical wavelengths (590-890 nm). Therefore, LkCa 15 may serve an excellent laboratory for studying the interaction between infant planets and the protoplanetary disk structure they sculp.

Here, we present the results of new high-contrast NIR (1.6μm) polarization imaging carried out on the LkCa15 disk. The combination of the High Contrast Instrument for the Subaru Next Generation Adaptive Optics(HiCIAO; Tamura et al. 2006) and Polarimetric Differential Imaging (PDI) provides a high-contrast image that is unprecedented in quality at infrared wavelengths and enables us to both clearly confirm and quantitatively analyze the wide gap structure and the inner disk. We report the warped inner disk and discuss the potential origin of a gapped and warped disk around LkCa 15. The gapped and warped disk suggests the existence of a multiple planetary system.

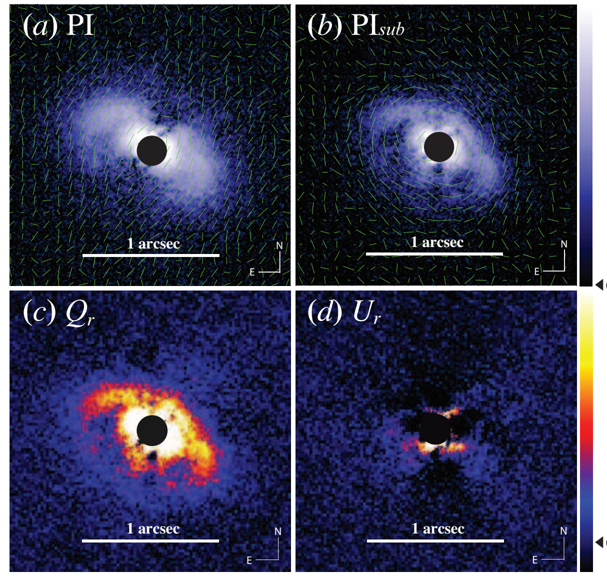

Fig. 1. *Top*: PI and overlapped polarization vector map images ($2.0'' \times 2.0''$) before (*a*) and after (*b*) halo subtraction. The saturated region is occulted by a software mask (r∼0.1″), the vectors are binned with spatial resolution, and the lengths are arbitrary for presentation purposes. (*a*): The effect of a polarized halo appears to have a tendency toward the minor axis of the disk. (*b*): The polarization tendency to the minor axis was removed, and the disk-origin polarization along the disk surface was revealed. *Bottom*: The radial Stokes Q_r (*c*) and U_r (*d*) images. In the Q_r image, both the outer and inner disks are significantly detected as expected from the PI image. On the other hand, the U_r image shows no disk-like component.

2 OBSERVATIONS AND DATA REDUCTION

The PDI observations of LkCa 15 were performed in the *H*-band on 2013 Nov 22 with HiCIAO on the Subaru Telescope combined with AO188 (Hayano et al. 2010). Each image has a 5″×5″ field of view (FOV) with a pixel scale of 9.5 mas/pixel. We obtained 17 data sets with 30 s exposure. The total integration time on the source of the polarization intensity image was 2040 s. All of our observations were conducted under the program of the SEEDS (Strategic Explorations of Exoplanets and Disks with Subaru; Tamura et al. 2009) project.

The polarimetric data were reduced in the standard manner of infrared image reduction that uses the custom IRAF[1] pipeline designed by Hashimoto et al. (2011). The Stokes *Q* and *U* images were obtained by the standard method for differential polarimetry (Hinkley et al. 2009). The polarized intensity (PI) image was obtained as $(Q^2+U^2)^{1/2}$. Because the convolved point spread function (PSF) cannot be perfectly removed by standard procedures, a residual stellar halo was sometimes observed in the obtained PI images. To remove the effect of this polarized halo, we constructed the polarization halo model by using the derived average polarization strength (0.67±0.03%) and average polarization angle (149.1±0.5°), and subtracted this from the Stokes *Q* and *U* images. From the halo-subtracted Stokes Q_{sub} and U_{sub} images, the final halo-subtracted PI$_{sub}$ image were generated (Figure 1b). To verify this result, we converted the coordinate system of Stokes *Q* and *U* to the radial Stokes Q_r and U_r (Avenhaus et al. 2014), because the Stokes Q_r image must show scattering polarization similar to the PI$_{sub}$ image, while the Stokes U_r image should contain less or no scattered light from the disk.

The disk components are clearly visible in the Stokes Q_r image, whereas the Stokes U_r image does not show any circular structures and its signals are faint and noisy (Figure 1c and d). Therefore, we concluded that the final PI$_{sub}$ image is robust.

[1] The IRAF software is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

3 RESULTS

The final PI image of the LkCA 15 disk with a software mask (r∼0.1″) is shown in the right panel of Figure 1b and 2, and two elliptical disk structures are clearly resolved. The brightness of the northwest side is significantly brighter than that of the southeast side, and this characteristic crescent of brightness is consistent with the optical imaging results of Thalmann et al. (2015).

The elliptical shape could be due to the system's inclination

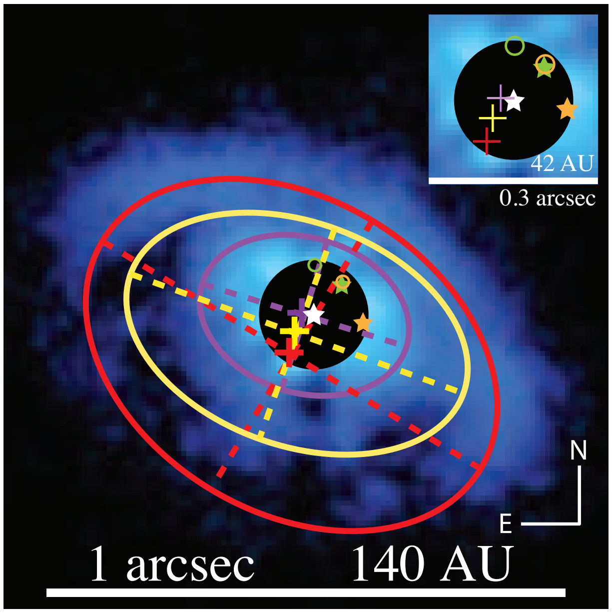

Fig. 2. Elliptical fitting results of the inner disk (*purple*), the gap (*yellow*), and the outer disk (*red*). The image has been smoothed by a gaussian with r=2 pixels to reduce the effects of speckles on the inferred structure of the disk. The central region is also shown in the right top panel. *White star* indicates the location of LkCa 15. *Green and orange stars* indicate where the planet candidates LkCa 15 b and c were detected in 2014, respectively (Sallum et al. 2015). *Empty green and orange circles* indicate the locations of two infrared sources seen in 2009-2010 (Kraus & Ireland 2012), which are assumed as LkCa 15 b and c, respectively.

(i). Thus, we fitted elliptical isophotes on a resulting image in order to measure the inclinations and position angles (PAs) of each disk. The elliptical fitting results are shown in Figure 2 and Table 1. We discovered new significant misalignments from major axis PAs of the two disks and gap (13±4°). The center of all three disk components appear on southeast side from the central star. The inclinations of the two disks are similar (∼44°), but that of the gap shows larger angle (∼52°). Note that Thalmann et al. (2014) reported eccentricities from the shape of the gap associated with LkCa 15, thus the inclination based on the ellipse fit only could be biased.

Figure 3 shows the radial surface brightness profiles on the major and minor axes with a power-law fit at each slope. In the profiles of major axes (top two profiles in Figure 3), the gap appears as a depletion in the middle of each profile. The slopes of the gap regions in profiles show a significant change between northeast and southwest axes (power indices r=2.0 and 1.2, respectively), and the slopes of the disk regions also show a change between inner and outer disks (r=-2.5 for inner disks, r=-3.1 and -3.6 for outer disks).

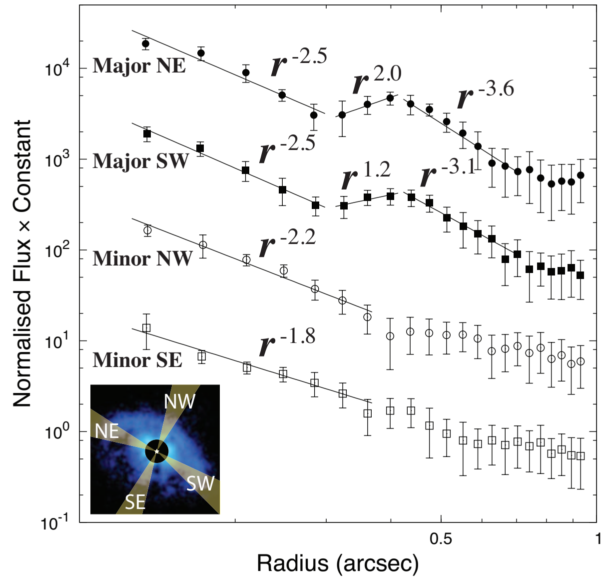

Fig. 3. Radial surface brightness profiles with 1σ error bars at major and minor axes. The values were measured at each axis within the range of ±10° (Yellow regions in left bottom panel), and were binned with a width of dr=4 pixels. The typical error of of power index is ∼0.05.

Table 1. Elliptical fitting results of two disks and gap[a].

Parameter	Outer Disk	Gap	Inner Disk
r_{major} (AU)	59.0±1.4	48.3±0.7	29.8±2.0
PA_{major} (°)[b]	59±2	67±3	72±2
i (°)[c]	44±1	51±2	44±2
Center (mas)[d]	(-37±4,-83±6)	(-24±6,-42±6)	(-13±2,-8±2)

[a] The peak, bottom, and half maximum positions (for the outer disk, gap, and inner disk, respectively) were obtained first from the radial profile at position angles every 10°. Then we conducted an elliptical fit by using the non-leaner least-squares Gauss-Newton algorithm with five free geometric parameters.
[b] Counterclockwise from north axis.
[c] Derived from the ellipticity. The inclination of a face-on disk is 0°, and that of an edge-on disk is 90°.
[d] (ΔR.A., ΔDec.). The origin of the coordinate corresponds to the position of the central star.

4 DISCUSSION

4.1 Disk Geometry: Which side is near to us?

We revisited the question of which side of the disk faces us. The brightness asymmetry of the disk could be a clue, but two explanations can be provided for that. The first is backward illumination of the gap wall; backward illumination indicates that the bright side is the wall of the far side of the gap (Quanz et al. 2011). The second is forward scattering, which indicates that the bright side is the surface of the disk's near side (e.g., Fukagawa et al. 2006). If backward illumination is the true explanation, the outer disk's inner edge would be optically thick and vertically high enough to conceal and reflect backward the light from the star. On the other hand, if forward scattering is the true explanation for this asymmetry, the inner edge of the outer disk would have a relatively low vertical height; therefore, more star light would arrive on the disk surface over the gap wall and more scattered light would come toward the observer. Therefore, both explanations are still under debate.

To try to elucidate which side faces us, we utilized the star-disk offset along the minor axis. On the projection of inclined disk, the central star comes to near side of the disk's minor axis (Dong et al. 2012). In Figure 2, the central star is roughly on the northwest minor axes of three disk components, therefore we can conclude that the northwest side of the disk of LkCa 15 could be the one facing us. This supports forward scattering as the explanation of the brightness asymmetry and is also consistent with 3D radiative transfer modeling (Thalmann et al. 2014).

4.2 Surface brightness behavior

We found the slope changes between northeast and southwest gaps, and between inner and outer disks. Furthermore, brightness slopes are not consistent with those of SPHERE/ZIMPOL results (power indices of inner disk, gap, and outer disk $\sim$ -2.4, 3.2 and -3.5 for northeast axis, -1.9, 2.1, and -4.1 for southwest axis, respectively, with typical error $\sim$ 0.1; Thalmann et al. 2015, private communication).

A number of reasons have been suggested to explain the change in brightness slopes, such as different extinction levels, surface densities, flaring angles or dust properties. The geological properties of inner disk could change the extinction level between the star and outer region and affect the brightness of outer disk (e.g., Krist et al. 2000); an actual change in the surface density slope can be translated into a change in the surface brightness slope, and a change of the flaring angle cause a change in the scattering of the disk's surface (e.g., Apai et al. 2004); a radial distribution of small dust particles and dust properties can affect the brightness slope (e.g., Akiyama et al. 2015). Although the brightness behavior could provide some physical properties of the disks, a detailed analysis on the reason of the brightness behavior is out of the scope of this letter, and it will be discussed elsewhere.

4.3 The origin of large gapped and warped disk

In the PI$_{sub}$ image and radial profiles, LkCa 15 has a large gapped (width $\sim$27 AU) disk. Among some mechanisms (e.g., grain growth, photoevaporation, disk-planet interaction; see Espaillat et al. 2014) that have been proposed to explain the clearing of the gaps in transitional disks, only gravitational interaction between disks and orbiting *multiple* planets can clear a *large* inner gap of $\gtrsim$ 15 AU or more (Zhu et al. 2011) and preserve optically thick inner disk. Furthermore, de Juan Ovelar et al. (2013) suggested a 1 $M_{\rm Jup}$ planet would create a similar size of outer gap edge at NIR and (sub-)mm wavelengths; conversely planets more massive than 1 $M_{\rm Jup}$ make different radial grain-size distribution in the dusty disk, and observations at different wavelengths capture different parts of grain-size distribution. Since the sizes of the outer gap edge of LkCa 15 are $\sim$50 AU in sub-mm (Piétu et al. 2006) and 48 AU at NIR (this work), a 1 $M_{\rm Jup}$ planet might create a gap around LkCa 15. By combining the upper mass limits of LkCa 15 companions, as Thalmann et al. 2010 suggested based on their imaging result, we concluded that assuming multiple planets with a mass of $\lesssim 1 M_{\rm Jup}$ could account for LkCa 15's large gapped disk with an outer gap edge similar in size at both NIR and (sub-)mm wavelengths.

We found a significant misalignment between two position angles of inner and outer disks (=13$\pm$4°) which indicates that the inner disk is possibly warped along the disk major axis. If inner disk was also warped along the minor axis, we would see misaligned inclination. However, the inclination of inner disk is consistent with that of outer disk ($\sim$44°). Warped disks, such as β Pictoris (e.g., Mouillet et al. 1997), AB Aurigae (Hashimoto et al. 2011) and HD 142527 (e.g., Marino, Perez, and Casassus 2015), have been reported on several stars surrounded by transitional disks and debris disks. These warped inner disks may be explained by the gravitational perturbation from planets (e.g., Mouillet et al. 1997). β Pictoris, whose planetary mass companion β Pictoris b has a similar inclination to and possibly responsible for the inner warped disk (e.g., Lagrange et al. 2012), is a possible evidence for this scenario. Additionally, Ahmic, Croll and Artymowicz (2009) also suggested the possibility of multiple planets in β Pictoris to explain warped disks.

To summarise, since LkCa 15 may possess multiple planets with a mass of $\lesssim 1 M_{\rm Jup}$ in the large gap, the warped inner disk could be the result of potential planets around LkCa 15.

5 CONCLUSION

We have presented a warped inner component beyond the large gap from the LkCa 15 disk system revealed by angular differential imaging in the *H*-band with HiCIAO installed on a Subaru Telescope. We derived 13$\pm$4° as the PA offset between the outer disk and the warped inner disk. This unique gap plus the warped disk configuration of the LkCa 15 system combined with the previous observations at mm and optical wavelengths indicates the existence of a multiple planetary system possibly composed of $\lesssim 1 M_{\rm Jup}$ planets on the solar system scale. To directly observe and reveal the origin and evolution of possible multiple planetary systems, future ground-based observations with the Extreme Adaptive Optics (ExAO) system such as the Subaru Coronagraphic ExAO (SCExAO; Jovanovic et al. 2015) are required.

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