Subaru Near-infrared Imaging Polarimetry of Misaligned Disks around the SR 24 Hierarchical Triple System*

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Abstract

The SR 24 multistar system hosts both circumprimary and circumsecondary disks, which are strongly misaligned with each other. The circumsecondary disk is circumbinary in nature. Interestingly, both disks are interacting, and they possibly rotate in opposite directions. To investigate the nature of this unique twin disk system, we present 0′′1 resolution near-infrared polarized intensity images of the circumstellar structures around SR 24, obtained with HIRES mounted on the Subaru 8.2 m telescope. Both the circumprimary disk and the circumsecondary disk are resolved and have elongated features. While the position angle of the major axis and radius of the near-IR (NIR) polarization disk around SR 24S is 55° and 137 au, respectively, those around SR 24N are 110° and 34 au, respectively. With regard to overall morphology, the circumprimary disk around SR 24S shows strong asymmetry, whereas the circumsecondary disk around SR 24N shows relatively strong symmetry. Our NIR observations confirm the previous claim that the circumprimary and circumsecondary disks are misaligned from each other. Both the circumprimary and circumsecondary disks show similar structures in $^{12}$CO observations in terms of its size and elongation direction. This consistency is because both NIR and $^{12}$CO are tracing surface layers of the flared disks. As the radius of the polarization disk around SR 24N is roughly consistent with the size of the outer Roche lobe, it is natural to interpret the polarization disk around SR 24N as a circumbinary disk surrounding the SR 24Nb–Nc system.

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1. Introduction

Observationally, there are many young binary stars hosting a circumprimary disk misaligned with respect to either a circumsecondary disk, a circumbinary disk, or a binary orbital plane (e.g., HK Tau, Jensen & Akeson 2014; L1551 NE, Takakuwa et al. 2017; GG Tau, Aly et al. 2018; IRS 43, Brinch et al. 2016; GW Ori, Czekala et al. 2017; HD 98900, Kennedy et al. 2019). These circumprimary and circumsecondary disks are directly imaged as two single disks. More recently, another type of young misaligned disk is beginning to be observed. They are inner disks misaligned with respect to outer disks both surrounding a single transitional object (e.g., HD 142527, Casassus et al. 2015; HD 100453, Benisty et al. 2017, van der Plas et al. 2019, HD 143006, Benisty et al. 2018; HD 153344B, Stolker et al. 2016; DoAr 44, Casassus et al. 2018; J1604, Mayama et al 2012; Mayama et al. 2018). Even in an earlier stage of protostar evolution, a warped disk around the protostar IRAS 04368+2557 was discovered with the Atacama Large Millimeter/submillimeter Array (ALMA; Sakai et al. 2019).

Some promising mechanisms that have been claimed to address theoretically the origin of inner disks misaligned with respect to outer disks are as follows: (1) the rotation axis of the disk system is misaligned with respect to the magnetic field direction (e.g., Ciardi & Hennebelle 2010); (2) the anisotropic accretion of gas with different rotational axes (e.g., Bate 2018); and (3) a massive planet misaligned with respect to an outer disk tilting an inner disk (e.g., Nealon et al. 2019; Zhu 2019). In the third mechanism, the planet is assumed to be sufficiently massive to open a gap in the disk. Such planets can become misaligned with respect to an outer disk through secular interaction with an external misaligned companion (Lubow & Martin 2016; Martin et al. 2016), or through precessional resonances (Owen & Lai 2017). In both cases, the inner disk (within the planet/companion orbital radius) might become aligned to the orbital plane of the planet, thus becoming misaligned with respect to the outer disk.

Among misaligned disks observed thus far, ALMA observations have shed light on SR 24, the target of this study, because Fernández-López et al. (2017) suggest that the circumprimary disk is strongly misaligned (108°) with respect to the circumsecondary disk, and both disks possibly rotate in opposite directions as observed from Earth, in projection. Here, the target of this study is introduced.
their results show that the outer radius, inclination, and PA of the circumprimary disk around SR 24S are $500^{+100}_{-150}$ au, 57°, and 25°, respectively.

Fernández-López et al. (2017) reported ALMA data and detected 1.3 mm continuum emission from SR 24N for the first time in this wavelength domain. The mass associated with the SR 24S and SR 24N disks is derived to be 0.025 $M_\odot$ and 4 $\times$ 10$^{-3}$ $M_\odot$, respectively. In addition, their $^{12}$CO(2-1) ALMA and SMA velocity cubes show three main features: (i) a gas reservoir extending north–northwest of SR 24N, (ii) a bridge of gas connecting SR 24N with SR 24S disks, and (iii) an elongated and blueshifted feature due southwest of SR 24S.

In the near-infrared (NIR), Mayama et al. (2010) resolved both circumprimary and circumsecondary disks around SR 24S and SR 24N, respectively. Their 0.01°1 observation detected a bridge of infrared emission connecting the two disks and a long spiral arm extending from the circumprimary disk.

Zhang et al. (2013) conducted H$_2$ NIR imaging observation to search for molecular hydrogen emission line objects. Although their observation covers an area of ~0.11 deg$^2$ toward the L1688 core in the ρ Ophiuchi molecular cloud including the area where SR 24 is located, they do not detect any emission from SR 24.

As SR 24 is a complex hierarchical triple system, there are still many unanswered questions in this regard. Therefore, in this paper, we present high-resolution NIR polarimetric images of SR 24 south and north as data. High-resolution polarimetric imaging is a powerful tool to study the structure of protoplanetary disks. The rest of this paper is organized as follows. Observations and data reduction procedures are described in Section 2. The results and discussion are presented in Sections 3 and 4, respectively. Section 5 summarizes the conclusions.

2. Observations and Data Reduction

We performed polarimetry in the H band (1.6 μm) toward SR 24 using the high-resolution imaging instrument HiCIAO (Hodapp et al. 2006; Tamura et al. 2006) with a dual-beam polarimeter mounted on the Subaru 8.2 m Telescope on 2011 August 2. These observations are part of the high-contrast imaging survey, Strategic Explorations of Exoplanets and Disks with Subaru (SEEDS; Tamura 2009). The polarimetric observation mode acquires o-rays and e-rays simultaneously, and images with a field of view of 10″ × 20″ with a pixel scale of 9.5 mas pixel$^{-1}$. SR 24S was observed without an occulting mask in order to image the innermost region around the central star. The exposures were sequentially performed at four position angles (P.A.s) of the half-wave plate, which are P.A. = 0°, 45°, 22.5°, and 67.5°, in one rotation cycle to measure the Stokes parameters. The integration time per wave plate position was 15 s, and the total integration time of the polarization intensity (hereafter PI) image was 1140 s. The adaptive optics system (AO 188; Hayano et al. 2010) provides a diffraction-limited and almost stable stellar point-spread function (PSF).

The Image Reduction and Analysis Facility software (IRAF$^{44}$) was used for data reduction. We follow the polarimetric data reduction technique described in Hashimoto et al. (2011) and Muto et al. (2012), in which the standard approach for polarimetric differential imaging (Hinkley et al. 2009) was adopted. By subtracting two images of extraordinary and ordinary rays at each wave plate position, we obtained $+Q$, $-Q$, $+U$, and $-U$ images, from which $2Q$ and $2U$ images were obtained through another subtraction to eliminate the remaining aberration. The instrumental polarization of HiCIAO at the Nasmyth platform was corrected by following Joos et al. (2008).

3. Results

3.1. SR 24S Circumprimary Disk

The H-band PI image of SR 24S after subtracting the polarized halo is presented in Figure 1(a). The polarized signal corresponds to stellar light scattered off the surface of small dust particles which are mixed with the circumstellar gas. Disk inner regions around SR 24S have appeared at 0″1. The bridge and spiral arm, which were detected in Mayama et al. (2010), are not detected with this observation, possibly owing to limited observation time which provided a modest signal-to-noise ratio (S/N). While the CIAO image in Mayama et al. (2010) revealed the outer part of the outer disk, the relatively inner part of the outer disk is mainly observed at this time in this PI image with HiCIAO. The circumstellar structure around SR 24S has elongated features both to the northeast and southeast directions.

Along the major axis, the PI on the northeast side is 7.6 times stronger than that on the southwest side at around 0″25 from the primary source. Along the minor axis, the PI on the southwest side is 3.7 times stronger than that on the northwest side at around 0″5 from the primary source. These show strong asymmetry along both the major and minor axes.

Figure 1(b) shows H-band polarization vectors superposed on the PI image. Although most of the circumprimary structures around SR 24S show a centrosymmetric vector pattern, the north–northwest and southwest circumstellar structures do not show such a pattern. Considering the separation between SR 24N and SR 24S, the deviation from a centrosymmetric polarization angle is probably because the circumstellar disk around SR 24S is partly illuminated also by SR 24N. The illumination from a relatively far star is reported around other young multiple systems. Krist et al. (1998), Hioki et al. (2011), and Gledhill & Scarrott (1989) suggested that the northern portion of the FS Tau circumbinary disk is illuminated by Haro 6–5 B located 20″ (2800 au) west of the FS Tau binary. Many polarization vectors around the FS Tau binary deviate from the larger centrosymmetric pattern in their maps. In addition, the azimuth angles of these two regions at the northwest and southwest of SR 24S are consistent with the disk regions connecting the north bridge and southwest spiral arm shown in Mayama et al. (2010). Therefore, these undetected bridge and arm structures might induce local polarization structures that deviate from the larger centrosymmetric pattern, disturbing the centrosymmetric polarization vector pattern around SR 24S.

Figure 2(a) shows the radial surface brightness profile of SR 24S along the major axis. In the northeast direction, the surface brightness along the major axis decreases as $r^{-1.8}$ from 0″4 to 1″2 and decreases as $r^{-1.1}$ from 1″3 to 1″4. In the southwest direction, the surface brightness along the major axis decreases as $r^{-1.1}$ from 0″4 to 0″6 and decreases as $r^{-0.3}$ from 0″7 to 0″8. Figure 2(b) shows the radial profile of the surface

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$^{44}$ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
brightness along the minor axis. In the northwest direction, the surface brightness along the minor axis decreases as $r^{-1.7}$ from 0\''2 to 0\''4 and decreases as $r^{-0.02}$ from 0\''5 to 0\''7. In the southeast direction, the surface brightness along the major axis decreases as $r^{-1.8}$ from 0\''2 to 1\''0. The typical error in the power-law index is $\sim 0.1$.

The radial profiles in the northeast direction along the major axis show a change of slope beyond 1\''2. Thus, our observations indicate that the NIR polarization disk seen in scattered light has a radius of 1\''2, while there are possible structures that are not illuminated by the central star beyond this NIR polarization radius. The derived semimajor axis is called “NIR polarization radius” in this paper. The P.A. of this NIR circumprimary disk is derived to be 55\° as it is the brightest angle.

3.2. SR 24N Circumsecondary Disk

Figure 1(c) shows the $H$-band PI image of SR 24N after subtracting the polarized halo. Figure 1(d) shows the polarization vectors overlaid on the PI image of SR 24N. SR 24Nb–Nc is not spatially resolved with our Subaru observations. This is because our 0\''1 resolution is not sufficiently high to resolve SR 24Nb–Nc. Based on an orbit calculated by Schaefer et al. (2018), the separation between SR 24Nb–Nc at the time of our observations in 2011 should be much smaller than 93.73 ± 1.58 mas, which was the closest in time to our Subaru observations and observed by Keck in 2014. In this paper, we consider SR 24Nb and SR 24Nc together as SR 24N and plot SR 24N with a green plus sign in Figures 1(c) and (d).

All of the circumsecondary structures around SR 24N show a centrosymmetric vector pattern in contrast to SR 24S. There are elongated emissions in the east–west direction. This elongated direction is nearly consistent with the CIAO observations. Figure 2(d) shows the radial surface brightness profile of SR 24N along the major axis. The error bars shown in Figure 2 represent the calculated standard deviation. In the western direction, the surface brightness along the major axis decreases as $r^{-2.1}$ from 0\''1 to 0\''3 and decreases as $r^{-1.0}$ from 0\''3 to 0\''8. In the east direction, the surface brightness along the major axis decreases as $r^{-2.0}$ from 0\''1 to 0\''3 and decreases as $r^{-0.7}$ from 0\''3 to 0\''8. Figure 2(e) shows the radial profile of the surface brightness along the minor axis. In the south direction, the surface brightness along the minor axis decreases as $r^{-1.6}$ from 0\''1 to 0\''3. In the north direction, the surface brightness along the minor axis decreases as $r^{-2.0}$ from 0\''1 to 0\''3.
The radial profiles in the east and west directions along the major axis show a change of slope beyond 0.3. Thus, our observations indicate that the NIR polarization disk seen in scattered light has a radius of 0.3, while there are possibly structures that are not illuminated by the central star beyond this NIR polarization radius. The P.A. of the circumsecondary disk is derived as 110°.

Figure 2(c) shows the azimuth-averaged radial surface brightness profile of SR 24S and SR 24N. The surface brightness of SR 24S decreases as \( r^{-1.5} \) from 0.2 to 1.0. The surface brightness of SR 24N decreases as \( r^{-2.1} \) from 0.1 to 0.3. The typical uncertainty of the measured power-law index is \( \sim 0.1 \). As shown in Figure 2(c), the azimuth radial surface brightness of SR 24N has a steeper profile than that of SR 24S. Our observations also show that the SR 24S disk is more spatially extended than the SR 24N disk.

4. Discussion

4.1. Circumbinary Disk Surrounding SR 24Nb–Nc

There appears to be a marginal detection of an arc-shaped structure emanating from the SR 24N circumsecondary disk as indicated by the blue dashed line in Figure 1(d). It begins at the west side of the SR 24N disk, extending north first, then curving to the northeast. The polarization vectors in the region of this arc structure face the central star SR 24N, indicating that this arc is not an artifact but a real structure illuminated by the central star and is physically connected to the outer edge of the circumsecondary disk associated with SR 24N. As this morphology is symmetric to the bridge emanating from the east side of the SR 24N disk also observed using both CIAO and Hubble Space Telescope (HST), this morphology might be attributed to binary formation.

Adopting the separation between Nb–Nc to be 0.16 as measured by HST observations and the mass ratio, \( q \), of 0.56 based on Correia et al. (2006), the size of the outer Roche lobe and the distance from SR 24Nb to the L2 point are derived as 0.31 and 0.26 in radius, respectively. As the measured radius, 0.3, of the polarization disk around SR 24N is roughly consistent with the computed size of the outer Roche lobe, it is natural to interpret the polarization disk around SR 24N detected with HiCIAO as a circumbinary disk surrounding the SR 24Nb–Nc system. The measured average distance to the arc-shaped structure is 0.26, and it is almost consistent with...
the computed distance to the L2 point. Thus, it is a plausible explanation that this arc-shaped structure is consistent with material leaking out the back door via the L2 point. Such a leakage of material occurs naturally from disks in binaries. The bridge structure emanating from the eastern side of the SR 24N disk can be observed to emanate beyond the size of the outer Roche lobe, indicating that the bridge structure is not attributed to the binary formation between Nb and Nc, but is attributed to the binary formation of the SR 24S–N system.

Schaefer et al. (2018) derived the P.A. and inclination of the SR 24Nb–Nc orbit to be 72°0 and 132°1, respectively, by calculating the orbit. As shown in Figure 3, Fernández-López et al. (2017) derived the P.A. and inclination of the secondary SR 24N CO disk to be 297° ± 5° and 121° ± 17°, respectively. Our derived NIR polarization disk P.A. of 110° is roughly consistent with the P.A. of the CO gas disk. This consistency is because both NIR and CO are tracing surface layers of the disks. Therefore, NIR and CO both traced the circumbinary disk surrounding SR 24Nb–Nc.

The continuum emission detected around SR 24N is unresolved by the ALMA observations at a resolution of 150 [mas] (Fernández-López et al. 2017). As its continuum disk size is much smaller than the SR 24Nb–Nc orbit, Schaefer et al. (2018) suggested that the continuum emission is likely from a circumstellar disk surrounding either Nb or Nc and is not from a circumbinary disk around SR 24Nb–Nc. Based on an orbit calculation by Schaefer et al. (2018), the angular semimajor axis of SR 24N is 181 [mas] (+83, −30). By using the estimate from Artymowicz & Lubow (1994), namely, the outer edge of a circumprimary disk should be truncated at around $r = 0.3–0.5$ times the semimajor axis, a maximum outer edge of the circumstellar disk is 90.5 [mas]. This size of the disk was not able to be resolved by the ALMA observation shown in Fernández-López et al. (2017). Therefore, the current estimate of circumstellar disk edge agrees with the estimate from Artymowicz & Lubow (1994).

4.2. Asymmetric Disk

Andrews et al. (2010) presented SMA 880 µm continuum observations of SR 24S with a resolution of 0″37 and resolved a disk. Their inset image of the SR 24S disk revealed a resolved central emission cavity with an apparent brightness enhancement to the northeast direction. According to their model fitting to the visibility at 880 µm, the cavity radius is 32 au (Andrews et al. 2010) or 29 au (Andrews et al. 2011).

Based on cycle 0 ALMA 0.45 mm continuum observations, van der Marel et al. (2015) modeled the SR 24S disk and derived that its disk P.A., inclination, and cavity radius are 20°, 45°, and 25 au, respectively. They also presented a 12CO channel map for SR 24S, which indicates that the southwest side is moving to the far side, whereas the northeast side is moving to the near side. The zero-moment 12CO $J = 6–5$ line map in Figure 1 of their paper shows the CO disk extending to the northeast direction. The P.A. and size of their 12 CO disk are consistent with the corresponding values of our NIR polarization disk. Similar to the case of SR 24N, this consistency is because both NIR and CO are tracing surface layers of the disks.

Fernández-López et al. (2017) presented 1.3 mm continuum images at a resolution of 0″18 obtained from ALMA cycle 1 and 2 observations. The ring-shaped disk associated with SR 24S is resolved, and its semimajor axis, semiminor axis, P.A., and inclination are 0″70 ± 0″06, 0″50 ± 0″06, 212° ± 3°, and 44° ± 6°, respectively. They also derived the P.A. and inclination of 12CO disks around both sources as shown in Figure 3. For the primary, SR 24S, the P.A. and inclination are 218° ± 2° and 70° ± 5°, respectively. Based on their measurements and analysis, the SR 24S disk has its nearest side to the east and the SR 24N disk has its nearest side to the north. They suggest that the SR 24S disk rotates in the counterclockwise direction, whereas the SR 24N disk rotates in the clockwise direction.

The cycle 2 ALMA 1.3 mm continuum images of SR 24 with a resolution of 0″18 are reported by Pinilla et al. (2017).
The 1.3 mm continuum images of the SR 24S disk are described by a ring-like emission with a central cavity. Fitting by Pinilla et al. (2017) showed that the P.A., inclination, and peak radius for the SR 24S disk are $24^\circ30$, $46^\circ31$, and $0^\circ3$, respectively. They detected $^{13}$CO and C$^{18}$O ($J = 2$–1) emission, both of which peaked at the center of the millimeter cavity associated with the SR 24S disk. Neither continuum nor gas emission from SR 24N is detected. A potential asymmetric shape on the SR 24S disk is inferred from the analysis in the visibility domain. In particular, both the north and south–southeast directions of SR 24S have strong emission in contrast with other directions.

Whereas the millimeter cavity around SR 24S with a radius of $\sim0^\circ3$ has been resolved by SMA and ALMA, it is not detected in our Subaru image. Thus, SR 24S possesses one of the “missing cavities” in NIR scattered light (Dong et al. 2012). Companion–disk interaction combined with dust filtration has been put forward as a likely explanation for such cavities (Zhu et al. 2012; Dong et al. 2015). Planet-opened gaps can reach a variety of depth depending on the planet mass, disk viscosity, and scale height (Fung et al. 2014). It is possible for gaps to be only modestly depleted in ~micron-sized dust, generally well coupled to the gas, and not prominent in scattered light. On the other hand, dust filtration (Rice et al. 2006) at the outermost gap edge can effectively stop millimeter-sized dust from entering the gap. Thus, such particles are drained in the inner disk, resulting in a prominent cavity in millimeter continuum emission. Photoevaporation may also open cavities in disks (e.g., Alexander & Armitage 2007). However, a low accretion rate onto the star ($<1e^{-8}M_\odot$ yr$^{-1}$) is expected in this scenario (Owen et al. 2012; Ercolano & Pascucci 2017), due to its inside-out nature. SR 24S has a high accretion rate of $10^{-7.15}M_\odot$ yr$^{-1}$ derived from the Paschen hydrogen recombination lines (Natta et al. 2006), and its cavity is unlikely to be produced by photoevaporation.

Figure 2(b) shows that the radial surface brightness decreases first around 0$''$5 then stops decreasing until 0$''$7 along the minor northwest axis. Figure 2(a) shows that the radial surface brightness decreases first around 0$''$75 then increases until 0$''$9 along the major southwest axis. According to Figures 2(a) and (b), both northwest and southwest radial surface brightness show a steeper slope whereas other directions show a gradual slope. The azimuthal direction of this NIR decrement structure is consistent with that observed in the submillimeter in Pinilla et al. (2017). A possible origin of this asymmetry is discussed in the next subsection.

4.3. Inner Disk Misaligned with Respect to an Outer Disk as an Origin of Asymmetry

Recently, Pinilla et al. (2019) reported ALMA band 3 observations at 2.75 mm for the SR 24S disk with an angular resolution of 0$''$11 × 0$''$09 and detected an inner disk. They observed that the inner disk emission is likely dominated by dust thermal emission instead of free–free emission. However, it is unclear whether the inner disk is misaligned with respect to the outer disk because the inner disk parameters such as P.A., inclination, and gas kinematic information are not derived.

Nixon et al. (2013) and Facchini et al. (2013) proposed a mechanism to generate a misaligned disk system: a binary on an inclined orbit with respect to its disk can break the circumbinary disk into inner and outer components, and cause the inner disk to press, resulting in a time-variant mutual inclination between the two disks.

By comparing Subaru NIR and ALMA dust and gas observations with 3D smoothed particle hydrodynamics (SPH) simulation shown in Facchini et al. (2018), we interpret that the SR 24S disk asymmetry is caused by the misaligned inner disk with respect to the outer disk based on the following two points.

(i) Scattering image: there are two constricted regions toward the north and southwest directions (P.A. = 0$^\circ$ and 225$^\circ$) in the Subaru NIR scattering image. While both sides of the circumprimary disk along the minor axis show mostly a symmetric distribution in the 1.3 mm dust continuum, only the northeastern and southern sides of the circumprimary disk in the NIR scattering image are bright. This morphology can be observed in Figure 4(b).

(ii) Dust continuum: the S/N at both 0.45 and 1.3 mm continuum images of the SR 24S disk shows that the west side...
of the ring has a slightly weaker emission compared with the east side of the ring (Pinilla et al. 2017). This asymmetry is consistent with Figure 13(j) in Facchini et al. (2018).

As compared in (i) and (ii), the stages of the 3D SPH simulations shown in Facchini et al. (2018) shared common features with the observed images in the NIR and continuum. This consistency between observations and simulation suggests that the observed asymmetry on the circumpri-
mary disk SR 24S in NIR scattered light might be affected by the inner disk being misaligned with respect to the outer disk.

A comparison between the 3D SPH simulation by Facchini et al. (2018) and observations also provides constraints on the inclination of the inner disk. We compared Figure 8 for the $\xi = 74^\circ$ case and Figure 9 for the $\xi = 30^\circ$ case in Facchini et al. 2018. ($\xi$ denotes the misalignment angle between the inner and outer disks). In particular, the (i), (j), (k), and (l) panels in both Figures 8 and 9, which have an outer disk inclination of 45°, are compared because previous submillimeter dust continuum observations revealed that the SR 24S outer disk has an inclination of approximately 45°. The outer disk shows a relatively axisymmetric structure, with two azimuthal regions of lower surface brightness for the $\xi = 74^\circ$ cases. For the $\xi = 30^\circ$ cases, in contrast, the outer disk shows a relatively nonaxisymmetric structure, with one side being much brighter than the other. In addition, there are relatively less clear signatures of pairs of azimuthal intensity decrements at near-symmetric locations in contrast with the $\xi = 74^\circ$ cases. As our NIR image has a similar asymmetric structure, the inclination of the inner disk can be constrained to close to $\xi = 30^\circ$ cases in contrast with $\xi = 74^\circ$ cases.

Finally, the leading formation mechanism of the misaligned inner disk with respect to the outer disk around SR 24S is discussed here. As introduced in Section 1, there are mainly three promising mechanisms that claim to address theoretically the origin of misalignment between an inner and an outer disk: (1) the rotation axis of the disk system is misaligned with the magnetic field direction; (2) the anisotropic accretion of gas with different rotational axes; and (3) a massive planet misaligned with respect to an outer disk tilting an inner disk. To discuss the leading formation mechanism of an inner disk misaligned with respect to outer disks in the SR 24S case and provide constraints to these mechanisms, we list some observational results below.

As discussed above, the misalignment angle between the inner and outer disks can be constrained to close to $\xi = 30^\circ$ in contrast with $\xi = 74^\circ$. The third mechanism starts from a small misalignment angle between an inner and outer disk and eventually produces a large misalignment angle, whereas the first mechanism can only produce small misaligned angles. Therefore, the first mechanism can be ruled out. Although no direct imaging observations have detected a companion inside the SR 24S cavity so far, the third mechanism triggered by an undetected massive companion embedded in the cavity could possibly tilt the inner disk of SR 24S. Subsequently, the second mechanism cannot be ruled out because the mass accretion rate of SR 24S and SR 24N is $10^{-7.17}$ and $10^{-6.90} M_{\odot}$ yr$^{-1}$ derived from the Paschen hydrogen recombination lines (Natta et al. 2006), respectively. In addition, the circumpri-
mary disk around SR 24S has a bridge and spiral arm. According to the numerical simulation in Mayama et al. (2010), fresh material streams along the spiral arm in which gas is replenished from a circummultiple reservoir and the bridge corresponds to gas flow and a shock wave caused by the collision of gas rotating around the primary and secondary stars. These structures, in particular the bridge, might contribute to the tilting of the outer disk around SR 24S. This is because the bridge is physically connecting the two circumpri-
mary and circumsecondary disks, which are strongly misaligned with one another. While it is difficult to provide further constraints on the origin of misalignment between the inner and outer disk with the currently available data, these mechanisms can be revealed using very-high-resolution observations such as ALMA in the future.

4.4. Binarity of SR 24S

The similarities between SR 24S and HD 142527 suggest the presence of a relatively massive companion. Price et al. (2018) and Lacour et al. (2016) demonstrated that the presence of such a companion can address various structures observed in the HD 142527 disk including a cavity, horseshoe, and so on. Therefore, we discuss the possibility that SR 24S may have an unseen companion.

As introduced in Section 1, the spectral type L2 and a luminosity of 12.9 $L_\odot$ of SR 24S are adopted here from Greene & Meyer (1995). Although the extinction correction of $A_V = 13.7$ mag is large, this would not change the conclusion. It is because that would not move SR 24S horizontally, but vertically, on the Hertzsprung–Russell diagram. Figure 5 shows that SR 24S is plotted along with the pre-main-sequence evolution tracks derived in Tognelli et al. (2011). This figure shows that the mass is slightly larger than 2.0 $M_J$. Because pre-main-sequence (PMS) star properties in both Greene & Meyer (1995) and Pecaut & Mamajek provide $T_{\text{eff}} = 5000$ K and 5040 K, respectively, log $t = 3.70$ is a reliable parameter. The mass of SR 24S is derived as 2.0 $M_J$ in Greene & Meyer (1995).

Consequently, taking all the uncertainties into account, it would be hard for SR 24S to have an equal-mass binary star. This is because the combined light would be cooler than a K2 star if SR 24S and its binary both have 0.9 $M_J$, for example. However, it is possible for SR 24S to have a companion which is smaller than 0.4 $M_J$, as the smaller mass companion would be from 1/10 to 1/20 the luminosity of the more massive star, SR 24S.

Furthermore, Pinilla et al. (2016) and Pinilla et al. (2019) used ALMA observation data and demonstrated that a massive planet ($<5 M_{\text{Jup}}$) could be present in the cavity of SR 24S while they excluded the possibility of existence of more massive planets ($>5 M_{\text{Jup}}$) in the cavity of SR 24S. The misalignment between the inner and outer disk surrounding SR 24S discussed in Section 4.3 might be attributed to this embedded massive companion. According to 3D numerical simulations by Nealon et al. (2018), for a planet massive enough to carve a gap, a disk is separated into two components and the gas interior and exterior to the planet orbit evolve separately, forming an inner and outer disk. Due to the inclination of the planet, a warp develops across the planet orbit such that there is a relative tilt and twist between these disks.

5. Summary

We have conducted high-resolution $H$-band polarimetric imaging observations of the enigmatic SR 24 triple system. The main conclusions are as follows:
1. The circumprimary disk associated with SR 24S is resolved and has elongated features both to the northeast and southeast directions. The P.A. and radius of the NIR polarization disk around SR 24S are 55° and 1″, respectively. The P.A. and size of the 12CO disk are consistent with the corresponding values of our NIR polarization disk. As the stages of the 3D SPH simulations shared common features with the observed images in the NIR, continuum, and 12CO, this consistency suggests that the observed asymmetry on the circumprimary disk might be due to the inner disk being misaligned with respect to the outer disk.

2. The circumsecondary disk associated with SR 24N is resolved and has elongated features in the east–west direction. The P.A. and radius of the NIR polarization disk around SR 24N are 110° and 0″3, respectively. The sizes and P.A.s derived from the NIR polarization and 12CO gas observations are consistent with each other. As the radius of the polarization disk around SR 24N measured to be 0″3 is roughly consistent with the computed size of the outer Roche lobe, it is natural to interpret the polarization disk around SR 24N detected with HiCIAO as a circumbinary disk surrounding the SR 24Nb–Nc system.

3. In the radial direction, the surface brightness of SR 24S and SR 24N decreases as $r^{-1.5}$ from 0″2 to 1″0 and $r^{-2.1}$ from 0″1 to 0″3, respectively. The azimuth radial surface brightness of SR 24N has a steeper profile than that of SR 24S. Our observations also show that the SR 24S disk is more spatially extended than the SR 24N disk.

4. As an overall morphology, the circumprimary disk around SR 24S shows strong asymmetry, whereas the circumsecondary disk around SR 24N shows relatively strong symmetry. Both the circumprimary and circumsecondary disks show similar structures to the 12CO gas disk in terms of size and elongation direction. This consistency is because both NIR and 12CO are tracing surface layers of the flared disks. Our NIR observations confirm the previous claim made through 0″2 submillimeter observations that the circumprimary disk is misaligned with respect to the circumsecondary disk.

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