From Interacting Binaries to Exoplanets: Essential Modeling Tools
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Direct Imaging of Bridged Twin Protoplanetary Disks in a Young Multiple Star

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Abstract. Protoplanetary disks are ubiquitously observed around young solar-mass stars and are considered to be not only natural by-products of stellar evolution but also precursors of planet formation. If a forming star has close companions, the protoplanetary disk may be seriously influenced. It is important to consider this effect because most stars form as multiples. Thus, studies of protoplanetary disks in multiple systems are essential to describe the general processes of star and planet formation.

We present the direct image of an interacting binary protoplanetary system. We obtained an infrared image of a young multiple circumstellar disk system, SR24, with the Subaru 8.2-m Telescope. Both circumprimary and circumsecondary disks are clearly resolved with a 0.1 arcsecond resolution. The binary system exhibits a bridge of infrared emission connecting the two disks and a long spiral arm extending from the circumprimary disk. A spiral arm would suggest that the SR24 system rotates counter-clockwise. The orbital period of the binary is 15,000 yr. Numerical simulations reveal that the bridge corresponds to gas flow and a shock wave caused by the collision of gas rotating around the primary and secondary stars. The simulations also show that fresh material streams along the spiral arm, confirming the theoretical proposal that gas is replenished from a circum-multiple reservoir. These results reveal the mechanism of interacting protoplanetary disks in young multiple systems. Furthermore, our observations provide the first direct image that enables a comparison with theoretical models of mass accretion in binary systems. The observations of this binary system provide a great opportunity to test and refine theoretical models of star and planet formation in binary systems.

Keywords. stars:binaries, stars:formation, stars:planetary systems: protoplanetary disks

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In a binary system, both the primary and secondary stars in orbit around each other have circumprimary and circumsecondary disks, respectively, and the entire system is surrounded by a circumbinary disk. Numerical simulations demonstrate that the stability of a protoplanetary disk in a multiple system is seriously jeopardized (Artymowicz & Lubow 1994). In simulations, despite the dynamical interactions between disks and stars, individual circumstellar disks can survive and large gaps are produced in the circumbinary disk. A circumbinary disk can supply mass to the circumstellar disks through a gas stream that penetrates the disk gap without closing it. Therefore, this infalling material through the spiral arm plays an important role in the formation of circumstellar disks.

However, such circum-multiple disks and spiral arms in multiple systems have never been directly imaged or resolved to date. Here, we report (Mayama *et al.* 2010) and analyse an infrared image of a young multiple system with bridged twin disks obtained with the adaptive optics (AO) (Takami *et al.* 2004) coronagraph CIAO (Tamura *et al.* 2000) mounted on the Subaru 8.2-m Telescope. In our study, we investigate the geometry of a multiple circumstellar disk system to understand its nature based on observation and numerical simulation. We study the hierarchical multiple SR24, located in the Ophiuchus star forming region at a distance of 160 pc (Chini 1981), composed of the low-mass T Tauri type stars SR24S (primary) and SR24N (secondary). SR24S is a class II source (stellar age of 4 Myr; Andrews & Williams 2007) of spectral type K2, with a mass of $>1.4\ M_{\odot}$ (Correia *et al.* 2006), where $M_{\odot}$ is the mass of the Sun. SR24N is located 810 AU north of SR24S (Correia *et al.* 2006) and is itself a binary system composed of SR24Nb and SR24Nc, with a projected separation of 30 AU (Correia *et al.* 2006). The spectral type and mass of SR24Nb are K4-M4 and 0.61 $M_{\odot}$, respectively (Correia *et al.* 2006). Those of SR24Nc are K7-M5 and 0.34 $M_{\odot}$, respectively (Correia *et al.* 2006). Because the separation between SR24Nb and SR24Nc is comparable to the angular resolution and is much smaller than that between SR24N and SR24S, we handle SR24Nb and SR24Nc together in this paper as SR24N, with a mass of 0.95 $M_{\odot}$. Accordingly, we regard the SR24 system as a binary with a primary to secondary mass ratio of 0.68, assuming the mass of SR24S to be 1.4 $M_{\odot}$.

The left panel of Figure 1 shows the H-band (1.6 μm) image of SR24 overlaid with the Roche lobe contours, showing the effective gravitational potential of the binary. SR24S was occulted by a coronagraphic mask during the observations. The image shows the residual emission after the point spread function (PSF) was subtracted from SR24S and SR24N, revealing faint near-infrared nebulosity at a resolution of 0.1 arcsecond. The emission arises from dust particles mixed with gas in the circumstellar structures scattering the stellar light. Both circumprimary and circumsecondary disks are clearly resolved, the first time these have been imaged for a young stellar binary. The primary disk has a radius of 420 AU and is elongated in the northeast-southwest direction. The secondary disk has a radius of 320 AU and is elongated in the east-west direction. Both disks overflow the inner Roche lobes (dotted contours in the figure), which show the regions gravitationally bound to each star, suggesting that the material outside the lobes can fall into either of the inner lobes. A curved bridge of emission is seen, connecting the primary and secondary disks. This emission begins at the southeast of the secondary disk, extending to the south while curving to the west, and reaches the north edge of the primary disk. This suggests a physical link, such as a gas flow between the two disks. Another salient feature is a broad arc starting from the southwestern edge of the primary disk, extending to the southeast through the Lagrangian point L3. Its tail is at least 1600 AU from SR24S. This emission is most likely a spiral arm and demonstrates that the SR24 system rotates counter-clockwise. The orbital period of the binary is 15,000 yr. The arm also implies replenishment of the twin disk gas from the circumbinary disk.

We performed 2D numerical simulations of accretion from a circumbinary disk to identify the features seen in the coronagraphic image. The right panel of Figure 1 shows a snapshot of the 2D simulations. The mass of SR24S is assumed to be 1.4 $M_{\odot}$ and the orbit is assumed to be circular, for simplicity. Although the gas flow is not stationary, especially inside the Roche lobes, the stage of the 2D simulations shown in Figure 1 shares common features with the observed image in the following two points. (1) A bridge is seen connecting the primary and secondary disks. It runs through the Lagrange point L1. (2)

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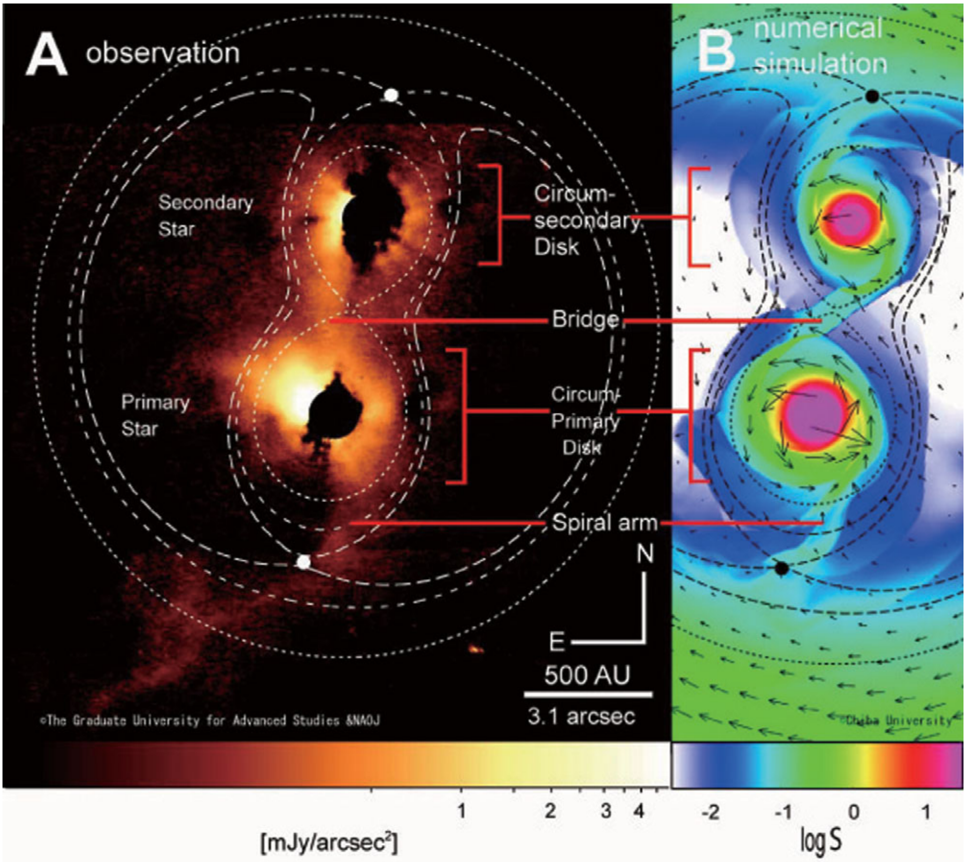

Figure 1. Observed and simulated images of the young multiple star, SR24. (A) H-band (1.6 μm) coronagraphic image of SR24. The PSFs of the final images have sizes of 0.1 arcsecond (FWHM) for the H-band. L1, L2, and L3 represent the inner Lagrangian point, outer Lagrangian point on the secondary side, and outer Lagrangian point on the primary side, respectively. (B) Snapshot of accretion onto the binary system SR24 based on 2D numerical simulations. The color and arrows denote the surface density distribution and velocity distribution, respectively.

A long spiral arm runs through the Lagrange point L3, with a pitch angle consistent with that of the observed spiral arm. These agreements suggest the following interpretations of the bridge and spiral arm associated with the SR24 system: The bridge corresponds to gas flow and a shock wave caused by the collision of gas rotating around the primary and secondary stars. The arm corresponds to a spiral wave excited in the circumbinary disk. Note that the bridge and spiral arm seen in the simulations are wave patterns and their shapes fluctuate with time.

Our observations provide the first verification of the theory that gas is replenished from the circumbinary disk to circumstellar disks, which was originally proposed by Artymowicz & Lubow (1996) but has not been confirmed by direct observations. Our direct imaging observations visualized the subsistent structures associated with a young multiple system which cannot be reproduced by spectroscopic observations or SED-model studies. Our research is the first observation of the mechanism of interacting protoplanetary disks in young multiple systems, and thus will contribute to a better understanding of star and planet formation in binary systems on the basis of subsistent morphology.

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Discussion

C. Clarke: This is beautiful work. Note that your simulations (which have rather a large ratio of sound speed to binary orbital velocity) are well matched to your observed system, which is wide (has a low orbital velocity). One would not expect to see the same bridge phenomenon if one was able to image close binary systems. So, this result should not be interpreted as evidence in favour of flow from secondary to primary in general.

C. Lee: How did you derive the masses of components?

S. Mayama: The masses of both components used in this study were from a previous observational study.

S. Daemgen: The simulations used a circumbinary disk. Are you able to see this disk in any of your observations?

S. Mayama: The circumbinary disk was out of the field of view of the SUBARU observations, but I believe that the southern arm is part of the circumbinary ring.

M. Montgomery: For the Northern Source, the radio knot center is off-center from the IR. Have they followed up with X-ray observations to see if jet is losing mass from observations?

S. Mayama: The literature to date says no.

S. Hinkley: How do you explain the brightness asymmetries in the post-subtraction image of your stars while the numerical model is very symmetric?

S. Mayama: The eastern part is brighter in both the circumprimary and circumsecondary disks. We interpret this as due to disk inclinations. We suggest that eastern part is the near side of the disk if we assume that forward scattering dominates, as is the case for Mie scattering of dust grains in the disks.