Strongly Misaligned Triple System in SR 24 Revealed by ALMA

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Abstract

We report the detection of the 1.3 mm continuum and the molecular emission of the disks of the young triple system SR24 by analyzing ALMA (The Atacama Large Millimeter/Submillimeter Array) subarcsecond archival observations. We estimate the mass of the disks (0.025 $M_\odot$ and $4 \times 10^{-5} M_\odot$ for SR24S and SR24N, respectively) and the dynamical mass of the protostars (1.5 $M_\odot$ and 1.1 $M_\odot$). A kinematic model of the SR24S disk to fit its C$^{18}$O (2-1) emission allows us to develop an observational method to determine the tilt of a rotating and accreting disk. We derive the size, inclination, position angle, and sense of rotation of each disk, finding that they are strongly misaligned (108°) and possibly rotate in opposite directions as seen from Earth, in projection. We compare the ALMA observations with $^{12}$CO SMA archival observations, which are more sensitive to extended structures. We find three extended structures and estimate their masses: a molecular bridge joining the disks of the system, a molecular gas reservoir associated with SR24N, and a gas streamer associated with SR24S. Finally, we discuss the possible origin of the misaligned SR24 system, concluding that a closer inspection of the northern gas reservoir is needed to better understand it.

Key words: accretion, accretion disks – ISM: individual objects (SR24) – stars: formation

1. Introduction

Multiple stellar and protostellar systems are commonly found in the Galaxy (e.g., Duchêne & Kraus 2013; Tobin et al. 2016, and references therein). Given the low probability of the stellar encounter and capture scenario in the average stellar density galaxy (Thies et al. 2005; Salyk et al. 2014), multiple systems primarily form via either turbulent fragmentation of the molecular cloud (e.g., Offner et al. 2010), fragmentation of an initially inhomogeneous rotating and infalling core (e.g., Boss & Keiser 2014), or fragmentation of a protostellar disk through gravitational instability (e.g., Stamatellos & Whitworth 2009; Vorobyov & Basu 2010; Kratter & Murray-Clay 2011).

If the multiple system is formed in a rotating core or a fragmenting massive disk, aligned co-rotating disks are expected, while in the case of turbulent fragmentation, a multiple system with misaligned disks can be formed (Bate 2000). A misaligned system can also be formed in a denser, more clustered environment, where gravitational interactions between its members or even captures of passing-by (proto)stars can become relevant. The infall of material with an odd angular momentum onto one of the protostellar disks of the multiple system may also produce a tilt on its inclination, leaving the system misaligned. Therefore, studying disk alignment can provide answers on how a young multiple system has formed.

A number of these misaligned young multiple systems have been observed. Optical polarimetric observations (e.g., Monin et al. 2006), misaligned outflows (e.g., Lee et al. 2016), direct imaging of disks (Stapelfeldt et al. 1998; Kang et al. 2008; Ratzka et al. 2009; Roccatagliata et al. 2011), and more recently, high-angular resolution of a disk’s gas kinematics (Jensen & Akeson 2014; Salyk et al. 2014; Williams et al. 2014) constitute the evidence for misaligned circumstellar disks in multiple systems. In addition, most of these systems are wide binaries (separations ≳100 au), suggesting the necessity of turbulent gas motions or gravitational interactions in their formation. In this contribution, we present ALMA millimeter observations toward the triple system SR24, showing that disks in this system are strongly misaligned and possibly counter-rotating in projection.

SR24 is a hierarchical triple system situated on the outskirts of the Ophiuchus molecular cloud ($d = 120$ pc, Loinard et al. 2008), southwest of clump E of L1688 (Struve & Rudjøbing 1949). The system comprises three T Tauri protostars (SR24S, SR24Nb, and SR24Nc, following the notation by Correia et al. 2006) with estimated spectral types and masses of K2, K4-M4, and K7-M5, and >1.4, 0.6, and 0.3 $M_\odot$, respectively (Correia et al. 2006). Their ages range $10^5$–$10^6$ year (Potter 2003). When convenient, we use SR24N to refer to the Northern close binary system, which, from 1991 to 2004, changed the projected separation between SR24Nb and SR24Nc from $0\farcs2$ to $0\farcs080$, rotating in a clockwise direction (proper motions measurements along four epochs can be found in Figure A.2 of the appendix A of Correia et al. 2006, and see also references therein). Likewise, SR24N is separated from SR24S by 5.08 (Reipurth & Zinnecker 1993) in a north–south direction. Infrared excesses (Greene et al. 1994), Hα emission and Li absorption (Martin et al. 1998), and 10 μm silicate emission (Nuemberger et al. 1998), all found toward SR24N and SR24S, are clear signposts of the presence of circumstellar accretion disks. Moreover, HST and H-band polarization intensity images (Potter 2003), along with a coronograph IR image of SR24 (Mayama et al. 2010) showed the emission due to the scatter of the stellar light in the circumstellar dust and gas of the SR24N and SR24S disks, with measured radii of $2\farcs0$ and $2\farcs6$, respectively. At millimeter wavelengths, only the continuum emission from SR24S has been detected (Reipurth et al. 1993; Andre & Montmerle 1994; Nuemberger et al. 1998; Pinilla et al. 2017), suggesting that only the warm dust at the inner part of the SR24N disk is still...
present while lacking the cold circumstellar dust of the outer part. Recent high-angular resolution (sub)millimeter observations of the SR24S circumstellar disk (Andrews & Williams 2005; Patience et al. 2008; Isella et al. 2009; Andrews et al. 2010; Ricci et al. 2010; Pinilla et al. 2017) unveiled the presence of an \( \sim 0.025 \) cavity at its center, making it a good candidate for an insight study on transitional disks. Molecular CO observations also detected the emission from the SR24S disk (Andrews & Williams 2005; Patience et al. 2008; Isella et al. 2009). The detected width of the CO (2-1) disk line is \( \sim 2 \) km s\(^{-1} \), indicating the presence of a moderately inclined disk (Isella et al. 2009). Additionally, slightly north of the SR24N position, there is a CO molecular extended source, which probably covers the molecular emission from the SR24N disk. Interestingly, this source is stronger than the CO emission coming from the SR24S position (Andrews & Williams 2005). Other environmental features that have been reported via optical and infrared scattered light observations (Potter 2003; Mayama et al. 2010) include: (i) a bridge between the two disks that expands and bifurcates into a filamentary structure, and (ii) a proposed spiral arm southwest of the SR24S disk.

The paper is organized as follows. In Section 2, we describe the ALMA observations. In Section 3, we present the main results obtained from the ALMA observations. In Section 4, we discuss our findings. Finally, in Section 5, we make a summary of this work.

2. Observations

2.1. ALMA Archive Observations

The data analyzed here come from two observations taken in the ALMA Cycle 1 (projects 2013.1.000912.S and 2013.1.000498.S). These projects focused on the study of the SR24S disk properties as inferred from the 1.3 mm (227 GHz) continuum and several CO isotopologues. Here, we explain the geometry of the disks using the continuum emission and the \(^{12}\text{CO}\) (2-1) and \(^{13}\text{CO}\) (2-1) lines. We also discuss the nature of the \(^{12}\text{CO}\) (2-1) extended emission in the SR24 triple system.

We built a 1.3 mm continuum image and a C\(^{18}\)O (2-1) velocity cube using the data collected on 2015 September 26 (project 2013.1.000912.S). The time on source was 23.3 minutes. At that time, ALMA had 34 operative antennas with baselines ranging up to 2270 m. During the observations, the median system temperature was about 70 K. The phase center was at \((\alpha, \delta)\) J2000.0 = \((16^h26^m58^s.5, 24^d45'35".87)\), and the FWHM of the primary beam of the telescope was 27" at the observing frequency. The ALMA digital correlator was set to have two continuum windows (2000 MHz width) and two additional spectral windows (1875 MHz width), most of which where line-free and were hence added to the continuum after removing the line channels. The four windows were centered at 219.550, 220.383, 234.507, and 232.987 GHz. Observations of the asteroid Pallas were used to set the absolute scale for the flux density calibration. The quasar J1517–2422 was used to correct for bandpass and the quasar J1617–2537, observed every 10 minutes, was used to extract the time-dependent gains and calibrate the phases and amplitudes. We self-calibrated and cleaned the final continuum image three times and applied a mask surrounding the two main sources detected in SR24. The data were calibrated, imaged, and analyzed using CASA (McMullin et al. 2007), KARMA (Gooch 1996), MIRIAD (Sault et al. 1995), and GILDAS\(^4\) packages. The final 7.5 GHz continuum image was obtained using natural weighting. Its synthesized beam is \(0.18 \times 0.12\) with a P.A. = 71°5' and its rms noise level is 44 \(\mu\)Jy beam\(^{-1}\). The \(^{18}\text{O}\) (2-1) velocity cube was obtained after applying the selfcal solution. The synthesized beam of the \(^{18}\text{O}\) data is \(0.21 \times 0.16\) with a P.A. = 76°6' and an rms noise level of 1.2 mJy beam\(^{-1}\) per 0.35 km s\(^{-1}\) channel.

The \(^{12}\text{CO}\) (2-1) data set was obtained on 2015 July 21 (project 2013.1.000498.S). SR24 was observed with 44 ALMA 12 m antennas for 12.6 minutes, with 946 baselines ranging from 15.1 to 1600 m. During the observations, the median system temperature was about 95 K. The phase center was at \((\alpha, \delta)\) J2000.0 = \((16^h26^m58^s.499, -24^d45'37".42)\). The ALMA correlator setup included eight spectral windows ranging in frequency from 215 to 233 GHz. One of these windows, centered at 230.714 GHz, covers 469 MHz and contains the \(^{12}\text{CO}\) (2-1) transition \(v_{\text{rest}} = 230.538 \) GHz. This spectral window has 1920 channels, providing a spectral resolution of 244 kHz, which results in 0.3 km s\(^{-1}\) at the observing frequency. In this case, Saturn’s moon Titan was used as the absolute flux calibrator and the quasars J1517–2422 and J1627–2426 were used to get the bandpass and the gains corrections, respectively. CASA, KARMA, and MIRIAD were again used to calibrate, image, and analyze the \(^{12}\text{CO}\) data. Two \(^{12}\text{CO}\) velocity cubes were obtained. The first velocity cube was obtained after applying a uv-taper to stress the extended \(^{12}\text{CO}\) emission. This image has a synthesized beam size of \(0.60 \times 0.54\) with a P.A. = 89°2', and it has an rms noise level of 4.6 mJy beam\(^{-1}\) in the binned channels of 0.6 km s\(^{-1}\). A second velocity cube was made with a natural weighting, which results in a \(0.25 \times 0.21\) with a P.A. = 61°3', synthesized beam and an rms noise level of 5.2 mJy beam\(^{-1}\) per 0.6 km s\(^{-1}\) channel.

2.2. SMA Archive Observations

The observations were obtained with the Submillimeter Array\(^5\) during 2004 August 2, when the array was in its compact configuration. The data were taken with seven antennas and double-sideband receivers with an IF frequency of 225.494 GHz. The zenith opacity \((\tau)\) at 230 GHz measured with the NRAO tipping radiometer located at the Caltech Submillimeter Observatory was \(-0.1\), which indicates good weather conditions. The \(^{12}\text{CO}\) (2-1) millimeter line at a frequency of 230.538 GHz was centered in the upper sideband. The digital correlator of the SMA was configured with 2 GHz bandwidth in each sideband and a spectral resolution of 1.06 km s\(^{-1}\) (~0.8 MHz) per channel. The phase center was at \((\alpha, \delta)\) J2000.0 = \((16^h26^m58^s.5, -24^d45'36".67)\). Both objects SR24S and SR24N fall well inside of the SMA FWHM (57") for this wavelength. The total on-source integration time for SR 24 was 1.7 hr.

Observations of Uranus provided the absolute scale for the flux density calibration. The gain calibrators were the quasars J1743–038 and J1733–130, while Callisto was used for bandpass calibration. The uncertainty in the flux scale is estimated to be between 15% and 20%, based on the SMA monitoring of quasars.

\(^4\) GILDAS data reduction package is available at http://www.iram.fr/IRAMFR/GILDAS/

\(^5\) The Submillimeter Array (SMA) is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.
3. Results

3.1. Continuum Emission from the Disks

The left panel of Figure 1 shows the spatial distribution of the ALMA 1.3 mm continuum emission contours overlapped with an archival HST ACS 6000 Å image.\(^6\) As previously reported, the system SR24 consists of two circumstellar disks (SR24N and SR24S) imaged, for instance, at infrared wavelengths (Mayama et al. 2010). While SR24S is associated with a well-known millimeter continuum source (e.g., Andrews & Williams 2005; Pinilla et al. 2017), here we report for the first time the detection of SR24N in this wavelength domain. ALMA shows SR24S having a well-defined annular morphology. This ring of dust is seen as an annular ellipse in projection (see Table 1), with two brighter parts toward the Northwest and the Southeast. SR24N is unresolved with the ALMA resolution (\(\sim 0.15''\)) and its position coincides with the position of the 2MASS disk within the positional uncertainty (0.75'', see right panel of Figure 1). We measured a peak flux of 314 \(\mu\)Jy beam\(^{-1}\) (that is a 7\(\sigma\) detection) for the SR24N millimeter source, which has a size of the order of the angular separation of the binary contained in it (as measured by Correia et al. 2006). For comparison, an M or K spectral type star at the distance of the Ophiuchus molecular cloud would have a flux density\(^7\) of \(\lesssim 0.5\) \(\mu\)Jy beam\(^{-1}\).

Therefore, the detected millimeter source in SR24N is probably due to the dust emission from the protostellar disk(s). Assuming optically thin isothermal dust emission, a gas-to-dust ratio of 100, a dust opacity of 1.1 cm\(^2\) g\(^{-1}\) at 1.3 mm appropriate for dust with thin ice mantles (Ossenkopf & Henning 1994), an opacity spectral index with an exponent \(\beta = 0.4\) for both sources (Isella et al. 2009; Ricci et al. 2010; Pinilla et al. 2014), and a dust temperature of 30 K, we estimate a mass associated with the SR24N millimeter source of 4 \(\times 10^{-5}\) \(M_\odot\) or 13 \(\pm 7\) \(M_\oplus\) (where we have estimated the statistical error based on the uncertainty of the flux density and a 5 K uncertainty for the temperature). Using the same approximate values, for SR24S we obtain a mass of 0.025 \(\pm 0.007\) \(M_\odot\), which is in good agreement with previous estimates (e.g., Isella et al. 2009; Andrews et al. 2010, 2011).

3.2. \(^{12}\)CO Molecular Emission from the Disks

The \(^{12}\)CO molecular emission observed by ALMA in the SR24 system shows the kinematics of two gaseous rotating disks at the positions of SR24S and SR24N (Figure 2). The gas content and kinematics of the SR24N disk is reported here for the first time.\(^8\) Table 2 presents a summary of the properties of the disks found through the \(^{12}\)CO emission.

A southwest–northeast (red- to blueshifted emission, respectively) velocity gradient indicative of rotation is observed in SR24S at a position angle,\(^9\) P.A. = 218\(^\circ\) \(\pm 2\(^\circ\), ranging for about 16 km s\(^{-1}\). The disk rotation is centered at 4.4 km s\(^{-1}\) and the spectrum integrated over the disk shows a double peak, as it is stronger the redshifted one (Figure 3). In addition, four slightly blueshifted spectral channels close to the cloud velocity (which we found to be the channel at \(V_\text{cloud} = 4.8\) km s\(^{-1}\), because it shows the typical interferometric pattern when extended emission is missed) show a significant absorption over the SR24S ring disk. This radial velocity range coincides exactly with the kinematics of the cloud 33 of the \(\rho\)-Ophiuchus region in which the SR24 system is embedded (de Geus et al. 1990). This absorption is possibly affecting the results of our 2D-Gaussian fit, which would explain the different inclination obtained, 70\(^\circ\), with respect to that obtained by analyzing the continuum emission, 44\(^\circ\).

Centered at a different velocity (5.6 km s\(^{-1}\), that is 1.2 km s\(^{-1}\) away from that of SR24S), the fainter SR24N \(^{12}\)CO emission presents a velocity gradient. The red- to blueshifted emission gradient (west–east, respectively; Figure 3) goes along the P.A. = 297\(^\circ\) \(\pm 5\(^\circ\) with a velocity range of about 11 km s\(^{-1}\). The integrated spectrum over the northern disk also presents a skewed double-peaked profile, with a stronger redshifted peak most probably due to the cloud absorption as in SR24S. Because the SR24N disk is not detected in less optically thick molecular tracers, we used the available \(^{12}\)CO information to make an order-zero estimate of the dynamical mass of the system. The left panel of Figure 4 shows a position–velocity diagram taken along the major axis of the SR24N disk. For comparison, we overlapped three Keplerian rotation curves produced with central masses ranging between 0.1 \(M_\odot\) and 1 \(M_\odot\), which encompass the emission from the disk. Another crude estimate of the dynamical mass for SR24N can be made by using the expression \((M/M_\odot) = 0.00121 \times (\Delta v/\text{km s}^{-1}/2)^2 \times (r/\text{au})\), where the parameters are \(\Delta v = V_\text{range}\) and \(r\) is equal to the geometric mean of the sizes given in Table 2. The resulting mass, 0.8 \(M_\odot\), is in good agreement with the total mass of the close binary system (0.95 \(M_\odot\), Correia et al. 2006). Compared with it, the mass of the SR24N disk is negligible.

\(^6\) http://cfa-www.harvard.edu/~cqi/mircook.html

\(^7\) The astrometry of the downloaded HST image was wrong, so we applied an offset to the center of that image in order to match the position of the SR24N disk with its optical counterpart.

\(^8\) Assuming an effective temperature of \(T = 3700\) K and a radius of \(R = 0.8\) \(R_\odot\) it is possible to derive the flux density at \(\nu = 230\) GHz for a typical M or K star in the Ophiuchus cloud (\(d = 120\) pc) using

\[
S_\nu = \int_{\text{source}} I_\nu(\theta, \phi) \cos \theta d\Omega.
\]

For small circular sources \(S_\nu \approx \pi D^2 I_\nu\), where \(\theta\) is the angular size of the star and \(I_\nu\) is the specific intensity. In this case,

\[
\theta = \arcsin(R/d) \approx 1.51 \times 10^{-10} \text{ rad}
\]

and, using the Rayleigh-Jeans approximation,

\[
I_\nu \approx B_\nu \approx 2K\nu^2/\lambda^2 = 6.0 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}.
\]

With all of these values, the derived flux density is 0.43 \(\mu\)Jy.

\(^9\) Note that Andrews & Williams (2005) reported the detection of the SR24N disk in \(^{12}\)CO with the SMA, but a closer inspection of the coordinates of this source make it clear that the SMA emission stems from an extended source north of SR24N position.

\(^{10}\) Throughout this work, we have adopted the convention typically used in visual binary orbit determination (Heintz 1978; Jensen & Akeson 2014). The position angle (P.A.) is counted in degrees from North (0\(^\circ\)) through East (90\(^\circ\)), ranging from 0\(^\circ\) to 360\(^\circ\), pointing to the redshifted edge of the disk (ascending node). The inclination of the disk (orbit) with respect to the plane of the sky ranges from 0\(^\circ\) to 180\(^\circ\), being 90\(^\circ\) that of an edge-on disk. If the disk rotates clockwise the inclination is <90\(^\circ\); if it rotates counterclockwise, the inclination is >90\(^\circ\).
3.3. Simple Modeling of the SR24S Disk Kinematics

The C$^{18}$O (2-1) line emission is only detected toward SR24S and not SR24N. Although fainter than the $^{12}$CO line, its emission is more optically thin and is less affected by the cloud absorption (Pinilla et al. 2017). This is the reason why the C$^{18}$O (2-1) line is the best molecular proxy available to study the kinematics of the SR24S disk. We made a simple model of a rotating and accreting thin disk, which does not include radiative transfer, as the goal is to study the disk kinematics and geometry. The surface density is described by a tapered power law consistent with the theoretical predictions for accretion disks (Lynden-Bell & Pringle 1974; Hartmann et al. 1998; Facchini et al. 2017; Factor et al. 2017):

$$\Sigma_{\text{gas}}(r) = \Sigma_0 \left( \frac{r}{r_c} \right)^{-\gamma} \exp \left[ -\left( \frac{r}{r_c} \right)^{(2-\gamma)} \right]$$

where $\Sigma_0$ is proportional to the disk mass, $r_c$ informs about the radial extent of the gas disk, and $\gamma$ is the power law index that...
Table 1
Characteristics of the 1.3 mm Continuum Sources

| Source   | R.A.           | Decl.          | Flux Density (mJy) | Semior Axis (°) | Semiminor Axis (°) | P.A. (°) | b (°) | \( M_{\text{disk}} \) (\( M_{\odot} \)) |
|----------|----------------|----------------|-------------------|-----------------|---------------------|----------|-------|--------------------------------------|
| SR24S    | 10°26'58.504"  | -24°45'37.21'' | 211 ± 4           | 0.70 ± 0.06     | 0.50 ± 0.06         | 212 ± 3  | 44 ± 6 | 0.025 ± 0.001                       |
| SR24N    | 10°26'58.434"  | -24°45'32.24'' | 0.34 ± 0.07       | ...            | ...                | ...      | ...   | 4 × 10^{-4} ± 1 × 10^{-5}            |

Notes.

\(^{a}\) Deconvolved semimajor and semiminor axis of the ring-shaped disk.

\(^{b}\) Estimated from the major and minor axis lengths as the \( \arccos(R_{\text{maj}}/R_{\text{disk}}) \).

\(^{c}\) The disk mass is estimated assuming a typical gas-to-dust ratio of 100.

\(^{d}\) This disk is unresolved with the present ALMA resolution.

Table 2
\(^{12}\)CO Disks Properties

| Source   | Size \((b_{\text{maj}} \times b_{\text{min}}):\) P.A. | P.A. | i | \( V_{\text{center}} \) (km s\(^{-1}\)) | \( V_{\text{range}} \) (km s\(^{-1}\)) | \( V_{\text{peaks}} \) (km s\(^{-1}\)) | \( V_{\text{absorption}} \) (km s\(^{-1}\)) |
|----------|-------------------------------------------------|------|---|--------------------------------------|---------------------------------|---------------------------------|---------------------------------|
| SR24S    | 0°50 ± 0°06 × 0°17 ± 0°02: 41°                 | 218 ± 2 | 70 ± 5 | 4.4 ± 0.3                  | [−3.5, 12.4] | −0.3/6.0 | [2.2, 4.1] |
| SR24N    | 0°60 ± 0°10 × 0°31 ± 0°06: 111°                | 297 ± 5 | 121 ± 17 | 5.6 ± 0.3               | [−0.3, 10.5] | 1.6/7.3  | [2.2, 4.8] |

Note. Column 2: deconvolved FWHM of the semimajor and semiminor axis and position angle estimated from a 2D-Gaussian fit to the moment 0 image produced using the \( V_{\text{range}} \) specified in column 5. Column 3: estimated using a linear fit to the peak of the red- and blueshifted high-velocity channels. Column 4: derived from the semimajor and minor axis obtained in column 2. Column 5: measured from a Gaussian fit to the wings of the line profile integrated along the disk. Column 6: measured until no 3σ emission is detected in a velocity channel at the disk position. Column 7: velocities of the disk’s double-peak spectrum. Column 8: velocity range of the self-absorption feature.

\(^{a}\) Velocities are \( V_{\text{LSR}} \) and are not corrected by the cloud velocity.

Figure 3. \(^{12}\)CO integrated spectra over the two SR24 disks. The foreground cloud velocity at 4.8 km s\(^{-1}\) is marked by a vertical line. The spectra show a skewed asymmetric double-peak profile with the stronger redshifted peak, possibly due to foreground absorption.

we fixed to 0.8 following Andrews et al. (2010). We implemented the kinematics of the rotating and accreting disk using the Miriad tasks \textit{velmodel} and \textit{velimage} and convolved the model with a 2D-Gaussian to match the observed synthesized beam. To build up the velocity cube with \textit{velimage}, we assumed that both the rotation and the infall velocity have an \( r^{-0.5} \) radial dependence. Our model of the velocity cube has nine free parameters: peak intensity, disk center \((x_0, y_0)\), inclination with respect to the line of sight \( i \), the characteristic radius \( r_c \), the position angle P.A. (measured from north to east), the LSR velocity \( v_{\text{LSR}} \), the rotation velocity \( v_{\text{rot}} \), and the accretion velocity \( v_{\text{infall}} \) at a fiducial radius of 1" (120 au for the adopted distance). We used an optimization algorithm based on the AGA method developed by Cantó et al. (2009) to fit the observed velocity cube and ran it a 100 times in order to extract a standard deviation for the averaged parameters (Table 3).

Figure 5 shows the good agreement between the simple model and the \(^{13}\)CO (2−1) observed velocity cube, which displays the typical butterfly-shaped emission along the velocity channels, proper of a Keplerian disk. The blueshifted emission is located preferably toward the Northeast, while the redshifted emission is found toward the Southwest, with the velocity center estimated at 4.6 ± 0.2 km s\(^{-1}\). The inclination and position angle match the values found in Section 3.1 from the continuum emission, while the radius of the gaseous disk seems to be almost a factor of two larger than the radius of the dusty disk, which may be explained by differences in the optical depth of the CO line and the continuum emission (Facchini et al. 2017). The rest of the resulting parameters of the fit are summarized in Table 3. The model included the rotation velocity of the disk at a fiducial radius of 120 au \((v_{\text{rot}} = 3.2 ± 0.5 \text{ km s}^{-1})\), which we use to estimate the dynamical mass of the protostar \((M = v_{\text{rot}}^2r/G)\) of 1.5 ± 0.5\( M_{\odot} \). This mass makes a good fit to the position–velocity diagram taken along the disk’s major axis (at P.A. = 212°) shown in the right panel of Figure 4. Additionally, it is similar to the value of 2\( M_{\odot} \) reported by Andrews et al. (2010).

3.4. Molecular Extended Emission

The \(^{12}\)CO (2-1) ALMA and SMA velocity cubes show several regions of extended emission. The SMA data set has shorter baselines than the ALMA data set and therefore is more sensitive to extended emission; although, on the contrary, it has
a coarser spectral resolution. We present both velocity cubes overlapped in Figure 6. There are three main features that we point out: (i) a gas reservoir extending north–northwest of SR24N, (ii) a bridge of gas connecting SR24N with the SR24S disks, and (iii) an elongated and blueshifted feature due southwest of SR24S.

The northern gas reservoir spreads out 7′.5 east–west and extends for about 4′–5′ north of SR24N. It embraces the SR24N disk and is probably associated with it, as it is detected from 5.4 to 7.9 km s⁻¹, part of the redshifted velocities at which the SR24N disk is seen. The elongated ¹²CO bridge connecting SR24N and SR24S disks extends for ~5′.5 north–south. It is mainly detected between 5.4 and 6.0 km s⁻¹ with the SMA, although the ALMA observations also show a faint arc-like structure linking the northeast part of the SR24S ring-like disk, with the east edge of the SR24N disk and the Northern gas reservoir. There is another ¹²CO linearly elongated source due southwest from SR24S that is detected at blueshifted velocities ranging from −0.9 to 0.9 km s⁻¹.

We estimate the mass of the Northern gas reservoir and the gas bridge between the disks using the ¹²CO (2-1) SMA emission, assuming that the gas is in local thermodynamic equilibrium and its emission is optically thin. We derive them with the following expression:

\[ M / M_\odot = 1.03723 \times 10^{-4} \frac{Q(T_e) e^{(E_e/T_e)} d^2 \int S_d dv}{\nu^3 S \mu^2 (X_{CO}/X_{HI})}, \]

in which we adopt an excitation temperature \( T_e = 30 \) K, the partition function for the ¹²CO \( Q(30 \) K) = 1.29, the energy of the upper level of the ¹²CO (2-1) transition is \( E_u = 16.596 \) K, the fractional abundance \( X_{CO}/X_{HI} = 10^{-4} \), the distance is \( d = 0.12 \) kpc, the rest frequency \( \nu = 230.538 \) GHz, the molecular dipolar momentum \( S \mu^2 = 0.02423 \) D, and the integrated flux density \( \int S_d dv \) goes in Jy km s⁻¹. The resulting masses, \( 13 \times 10^{-7} M_\odot \) and \( 2 \times 10^{-7} M_\odot \) (see Table 4), for the Northern reservoir and the bridge, respectively, are of the order of half the mass of the planet Earth.

## 4. Discussion

### 4.1. Geometry of the Disks

Having measured the P.A. and the inclination of a disk, the only information that is missing to completely characterize its geometry is to know the tilt of the protostellar disk (i.e., which end of the disk’s minor axis is the nearest to the observer). This could be addressed indirectly by putting together the information about the approaching–receding side of the disk and the sense of the disk’s rotation (an analogous problem to distinguish between leading and trailing spiral arms in galaxies, e.g., de Vaucouleurs 1958; Repetto et al. 2017).
For SR24S, the southwest side of the disk is receding (redshifted), while the northeast side is approaching (blue-shifted). We can now derive the sense of rotation (and hence the tilt of the disk) in three ways. The first is achieved by admitting the indications of previous coronograph IR observations (Mayama et al. 2010), which show an extended arc of emission reported as a spiral arm of the SR24S disk. The curvature of the spiral arm would indicate that the disk is rotating counterclockwise (as seen in projection), which implies that the east side is its near side. Second, the same infrared observations show brighter emission toward the east side of the SR24S disk, which lead Mayama et al. (2010) to conclude that the near side is the east side (the same applies also for the SR24N disk). Along with the approaching/receding kinematic information, this implies a counterclockwise rotation for the SR24S disk. The third evidence supporting...
Figure 7. SR24S position–velocity diagrams of the $^{13}$CO (2-1) emission made with two cuts perpendicular to the disk’s major axis (P.A. = 122°). Velocity is in LSR and positional offsets are with respect to the major axis of the disk. Contours are at −20%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of the maximum peak emission. The left panel shows the cut taken north of the central position and the right panel shows the cut taken south of it. The asymmetric boomerang-like features displayed are due to gas rotation and accretion.

Table 4

| Source          | Flux Density (Jy km s$^{-1}$) | Size (arcsec$^2$) | $M_{\text{BH}}$ ($\times 10^{-3} M_\odot$) |
|-----------------|------------------------------|-------------------|---------------------------------------------|
| Northern reservoir | 11.3 ± 0.3                   | 16.5              | 13                                          |
| Bridge          | 3.0 ± 0.1                     | 37.5              | 3                                           |
| Southern streamer | 1.6 ± 0.1                     | 7.0               | 2                                           |

Note. Column 2: integrated $^{12}$CO (2-1) flux densities from SMA observations with a synthesized beam of 2″0 × 1″5; P.A. = 42°2. Column 3: approximated size of the source taken from the SMA data set. Column 4: mass of the gas estimated from the SMA integrated flux measurements.

this sense of rotation comes from a close inspection of the velocity field of the C$^{18}$O disk. Figure 7 presents two different velocity cuts perpendicular to the major axis of the SR24S disk. A subtle asymmetric pattern can be noticed in both position–velocity diagrams. On one hand, the northern pv-cut shows the blueshifted emission in a boomerang-shaped feature originated by the rotation, but the west arm of the boomerang is shorter than the east arm. On the other hand, the southern pv-cut shows the redshifted emission in another boomerang-shaped feature, but this time, the east arm is slightly shorter and fainter. The asymmetric length of the boomerang arms in both pv-diagrams is due to the non-zero infall velocity as supported by the following study that we present using some synthetic models. Actually, the asymmetry is more pronounced as the infall velocity is larger and the disk is closer to edge-on. Note that if outflow rather than infall motions are considered, the asymmetry would be reversed. In the case of the SR24 system, we assume infall motions based on the evidence of accretion provided by Paschen hydrogen recombination lines observations by Natta et al. (2006).

In Figure 8, we show sketches for two rotating and accreting disks with inclinations separated by 180° and a third rotating disk with no accretion (Cases I, II, and III, respectively). We simulated the kinematics of these disks using the toy model described in Section 3.3 for SR24S but changing the inclination and the accretion velocity while keeping the receding and approaching sides of the observations fixed. Two position–velocity cuts perpendicular to the major axis of the disks are presented for each case. Case I and III disks have their nearest side to the east (inclination $i = 46^\circ$) and differ only in the accretion velocity: $v_1 = 3.2$ km s$^{-1}$ and $v_{\text{III}} = 0.0$ km s$^{-1}$. Case II disk has $i = 136^\circ$, $v_{\text{II}} = 3.2$ km s$^{-1}$ and its nearest side is west. Case I and II disks rotate in opposite directions (as seen in projection) so that they keep the receding and approaching sides the same. The pv-cuts perpendicular to the major axis of the disks show similar boomerang-shaped features as the SR24S observations. The boomerang shapes appear due to the gas rotation (Case III), but the asymmetries in the length of the boomerang arms are related to the accretion or infall motions (Cases I and II). Indeed, in the case of an accreting disk, the asymmetry pattern is also related with the inclination of the disk with respect to the plane of the sky. As evidenced by Figure 8, when $i < 90^\circ$ (Case I) the infall motions make the nearest blueshifted quarter of the disk to reach less blueshifted velocities, while the opposite applies for the farthest blueshifted quarter of the disk. Analogously, the farthest redshifted quarter appears less redshifted than the nearest redshifted quarter. On the contrary, when $i > 90^\circ$ (Case II) the asymmetries are just reversed, making it possible from the kinematic observations to determine which is the nearest side, the true inclination and the sense of rotation of the disk, given that the disk has infall motions. All of this analysis leads us to derive the sense of rotation (counterclockwise) and the location of the near edge (east edge) of the SR24S disk.

For the SR24N disk, the lower signal-to-noise ratio and the foreground cloud absorption of the $^{13}$CO data prevent a similar analysis. Therefore, we assume that the sense of the disk rotation matches that of the close binary systems SR24Nb and SR24Nc (i.e., clockwise, see section Section 1.
and Correia et al. 2006). Although there are examples of disks hosting counter-rotating stars (Bate et al. 2010; Vorobyov et al. 2016, and references therein), the simplest hypothesis is that both binary and disk rotate in the same sense.

Figure 9 sketches the SR24 system (note that it is not to scale and the gaps of the disks are not real), with the binary system SR24N rotating clockwise and with an inclination <90°, while the SR24S disk is rotating counterclockwise with an inclination >90°. Given the measured position angles and the inclinations of both disks (Tables 1–3), we derive an angle between the angular momentum vectors of the two disks of 108° ± 25°. Even considering that the SR24N disk rotates in the opposite direction (it would have i = 59°) the disk’s angular momentum vectors would be 66° away from each other. Therefore, there is

\[ D = \cos \Delta = \cos i_1 \cdot \cos i_2 + \sin i_1 \cdot \sin i_2 \cdot \cos(\text{PA}_1 - \text{PA}_2), \]

where \( i_1 \) and \( i_2 \) are the disk inclinations.

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**Figure 8.** Three cases of disks with different inclinations with respect to the plane of the sky and kinematics (sense of rotation and infall). We took the synthetic model for the SR24S disk, changed some parameters, and produced two associated position–velocity cuts perpendicular to its major axis (that is, with a P.A. = 122°) and centered north and south of the disk center. The pv-diagrams are displayed to the right of the corresponding disk sketch. In all three cases, the blueshifted emission is produced in the Northeast and the redshifted emission is in the Southwest. In Case I, the disk has an inclination of 45° (<90°), the near edge due east, a counterclockwise rotation \( (v_{rot} = 3.2 \text{ km s}^{-1}) \), and an infall velocity of 1.0 km s\(^{-1}\). In Case II, the disk inclination is 135° (>90°), the near edge is due west, it is rotating clockwise, and has an infall velocity of 1.0 km s\(^{-1}\). Finally, Case III shows the same disk as for Case I but without infall velocity. For all three models, \( v_{LSR} = 4.6 \text{ km s}^{-1} \).
strong evidence suggesting that the SR24 system has two highly misaligned disks.

4.2. Extended Gas Features

Inspecting the HST optical emission of Figure 1, it is noticeable the bridges and/or streamers produced by light scattered in dust and gas (Potter 2003). There is a twisted bifurcation in the bridge joining the SR24N and SR24S disks, and a prominent curved arc south of SR24S thought to be a spiral arm (Mayama et al. 2010). The present $^{12}$CO (2-1) observations from ALMA and SMA do not perfectly match these structures. For instance, the southern optical/infrared spiral arm has no $^{13}$CO counterpart. The location of the molecular bridge between the two disks (Figure 6) is slightly east of the HST bifurcated bridge, but both seem to join the two disks of the system. The nature of this bridge is unknown, although it is well known from numerical simulations that multiple systems have bridges of material like the one observed here (e.g., Gabbasov et al. 2017). We have also noticed that the optical bridge between the disks of the system has a curvature and joins the west side of SR24S with the east side of SR24N. Models including two disks with the same sense of rotation (see Figure 1 in Mayama et al. 2010) seem to predict a reversed orientation of the linking bridge, and this is a point for further investigation of the geometry and kinematics of the system.

Regarding the Northern gas reservoir seen in the $^{12}$CO (2-1) maps (Figure 6), it is possible that it is connected (in space and velocity) with the bridge. It could be part of a spiral structure due to gravitational instabilities of the system (see, e.g., Tobin et al. 2016), the remnant of a circumbinary structure, or a gas reservoir north of SR24N. There is a twisted bifurcation in the bridge joining the SR24N and SR24S disks, resulting in a tilt with respect to its original inclination. Regarding the existence of a gas reservoir north of SR24N, this may provide a plausible explanation for the misalignment in SR24, which may erase the memory of the formation mechanism in this system.

4.3. Origin of the SR24 System

The ALMA observations and the previous work on the SR24 system make it clear that the two disks are misaligned, making this one more of a small sub-population of multiple systems with large separations (Jensen & Akeson 2014; Salyk et al. 2014; Williams et al. 2014). However, SR24 has another peculiarity: the two disks possibly rotate in opposite directions as seen from Earth (i.e., in projection, one rotates clockwise and the other counterclockwise). How this system originated is not a trivial question, and here we introduce a few suggestions into the discussion.

It is known that a highly misaligned multiple system is hardly formed via the collapse of a non-turbulent rotating cloud, and this has been previously stated by numerical simulations (e.g., Bate et al. 2010). Such non-turbulent clouds may produce disks that can undergo further fragmentation due to gravitational instabilities, being the most recent and clear example the triple system L1448 IRS3B (Tobin et al. 2016). Therefore, a cloud would need some degree of initial turbulent motions as to fragment into (at least two) pieces that would finally rotate in highly misaligned, or even opposite directions (i.e., antiparallel spins Offner et al. 2010; Tokuda et al. 2014).

Another possible explanation for the formation of a system with two strongly misaligned disks is the event of a close encounter of two previously isolated protostellar disks. However, in the thorough analysis by Salyk et al. (2014), adapting the expressions of Thies et al. (2005) to the Ophiuchus molecular cloud, they estimate a low encounter probability ($<10^{-5}$) for impact parameters under 500 au.

Whatever the multiple system formation mechanism was, at some point, one of the protostellar disk companions may undergo an event of external accretion from a reservoir of material (Vorobyov et al. 2016), which may impinge a tilt in this particular disk, resulting in a tilt with respect to its original inclination. Regarding the existence of a gas reservoir north of SR24N, this may provide a plausible explanation for the misalignment in SR24, which may erase the memory of the formation mechanism in this system.

5. Summary and Conclusions

By using archival ALMA observations, we report the detection at 1.3 mm of the two protostellar disks toward the SR24 system, both in continuum and molecular emission ($^{12}$CO and C$^{18}$O 2-1 lines). We estimate the disk masses for SR24S and SR24N (0.025 $M_\odot$ and $4 \times 10^{-3} M_\odot$, respectively) and the dynamical masses for both protostars (1.5 $M_\odot$ and 1.1 $M_\odot$). We implemented a simple kinematic model to fit the velocity cube of the SR24S C$^{18}$O disk emission and completely determine the geometry of the disks, and we derive the possible sense of rotation and the angle between their angular momentum vectors. The disks are highly misaligned ($\sim$$108^\circ$) and are probably rotating in opposite directions, as seen from Earth.

We also use archival $^{12}$CO (2-1) SMA observations to show the extended molecular emission distribution. We detect a bridge of gas joining both disks (other bridge is observed in optical/infrared as well) and a gas reservoir north of SR24N. The true nature of this gas reservoir may be the key for
interpreting the formation of this system. If it is a remnant of a circumbinary disk or part of a spiral structure associated with SR24N, then the large misalignment between the disks may suggest a turbulent origin of the system; contrarily, if the gas reservoir is external to the system, it could well have been accreted by SR24N, tilting its original orientation, and thus erasing all of the information about the formation of this system (whether it was from the turbulent fragmentation of a cloud or the fragmentation of a disk).

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References

Anderson, P., & Montmerle, T. 1994, ApJ, 420, 837
Andrews, S. M., & Williams, J. P. 2005, ApJL, 619, L175
Andrews, S. M., Wilner, D. J., Espaillat, C., et al. 2011, ApJ, 732, 42
Andrews, S. M., Wilner, D. J., Hughes, A. M., Qi, C., & Dullemond, C. P. 2010, ApJ, 723, 1241
Bate, M. R. 2000, MNRAS, 314, 33
Bate, M. R., Lodato, G., & Pringle, J. E. 2010, MNRAS, 401, 1505
Boss, A. P., & Keiser, S. A. 2014, ApJ, 794, 44
Cantó, J., Curiel, S., & Martínez-Gómez, E. 2009, A&A, 501, 1259
Correia, S., Zinnecker, H., Ratzka, T., & Sterzik, M. F. 2006, A&A, 459, 909
de Geus, E. J., Bronfman, L., & Thaddeus, P. 1990, A&A, 231, 137
de Vaucouleurs, G. 1958, ApJ, 127, 487
Duchêne, G., & Kraus, A. 2013, ARA&A, 51, 269
Facchini, S., Birnstiel, T., Bruderer, S., & van Dishoeck, E. F. 2017, arXiv:1705.06235
Factor, S. M., Hughes, A. M., Flaherty, K. M., et al. 2017, AJ, 153, 233
Gabbasov, R., Sigalotti, L. D. G., Cruz, F., Klipp, J., & Ramírez-Velasquez, J. M. 2017, ApJ, 835, 287
Gooch, R. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 80
Greene, T. P., Wilking, B. A., Andre, P., Young, E. T., & Lada, C. J. 1994, ApJ, 434, 614
Hartmann, L., Calvet, N., Gullbring, E., & D’Alessio, P. 1998, ApJ, 495, 385
Heintz, W. D. 1978, Double Stars (Dordrecht: Reidel)
Isella, A., Carpenter, J. M., & Sargent, A. I. 2009, ApJ, 701, 260
Jensen, E. L. N., & Akeson, R. 2014, Natur, 511, 567
Kang, M., Choi, M., Ho, P. T. P., & Lee, Y. 2008, ApJ, 683, 267
Kratter, K. M., & Murray-Clay, R. A. 2011, ApJ, 740, 1
Lee, K. I., Dunham, M. M., Myers, P. C., et al. 2016, ApJL, 820, L2
Loinard, L., Torres, R. M., Mioduszewski, A. J., & Rodríguez, L. F. 2008, ApJL, 675, L29
Lynden-Bell, D., & Pringle, J. E. 1974, MNRAS, 168, 603
Martin, E. L., Montmerle, T., Gregorio-Hetem, J., & Casanova, S. 1998, MNRAS, 300, 733
Mayama, S., Tamura, M., Hanawa, T., et al. 2010, Sci, 327, 306
Mcmullin, J. P., Waters, B. S., Schiebel, D., Young, W., & Golap, K. 2007, in ASP Conf. Ser. 376, Astronomical Data Analysis Software and Systems XVI, ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 127
Monin, J.-L., Mérand, F., & Peretto, N. 2006, A&A, 446, 201
Natta, A., Testi, L., & Randich, S. 2006, A&A, 452, 245
Nuernberger, D., Brandner, W., Yorke, H. W., & Zinnecker, H. 1998, A&A, 330, 549
Öfner, S. S. R., Kratter, K. M., Matzner, C. D., Krumholz, M. R., & Klein, R. I. 2010, ApJ, 725, 1485
Ossenkopf, V., & Henning, T. 1999, A&A, 306, 943
Patience, J., Akeson, R. L., & Jensen, E. L. N. 2008, ApJ, 677, 616
Pinilla, P., Benisty, M., Birnstiel, T., et al. 2014, A&A, 564, A51
Pinilla, P., Pérez, I. M., Andrews, S., et al. 2017, ApJ, 839, 99
Potter, D. E. 2003, PhD thesis, Univ. Hawai‘i
Ratkza, T., Scheerer, A. A., Leinert, C., et al. 2009, A&A, 502, 623
Reipurth, B., Chini, R., Krugel, E., Kreysa, E., & Sievers, A. 1993, A&A, 273, 221
Reipurth, B., & Zinnecker, H. 1993, A&A, 278, 81
Repetto, P., Faúndez-Abans, M., Freitas-Lemes, P., Rodrigues, I., & de Oliveira-Abans, M. 2017, MNRAS, 464, 293
Ricci, L., Testi, L., Natta, A., & Brooks, K. J. 2010, A&A, 521, A66
Roccatagliata, V., Ratzka, T., Henning, T., et al. 2011, A&A, 534, A33
Salyk, C., Pontoppidan, K., Corder, S., et al. 2014, ApJ, 792, 68
Sault, R. J., Teuben, P. J., & Wright, M. C. H. 1995, in ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems IV, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes (San Francisco, CA: ASP), 433
Stamatellos, D., & Whitworth, A. P. 2009, MNRAS, 400, 1563
Stapelfeldt, K. R., Krist, J. E., Ménard, F., et al. 2001, ApJL, 550, L65
Struve, O., & Rudkjøbing, M. 1949, ApJ, 109, 92
Thies, I., Kroupa, P., & Theis, C. 2005, MNRAS, 364, 961
Tobin, J. J., Kratter, K. M., Persson, M. V., et al. 2016, Natur, 538, 483
Tokuda, K., Onishi, T., Saigo, K., et al. 2014, ApJL, 789, L4
Vorobyov, E. I., & Basu, S. 2010, ApJ, 719, 1896
Vorobyov, E. I., Regaly, Z., Guedel, M., & Lin, D. N. C. 2016, A&A, 587, A146
Williams, J. P., Mann, R. K., Di Francesco, J., et al. 2014, ApJ, 796, 120