

ALMA Band 6 high-resolution observations of the transitional disk around SY Cha

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Abstract

Transitional disks have a cavity with weak dust emission in the central region, and they are thought to be highly evolved protoplanetary disks. The formation mechanism of such disks is still not known. Transitional disks are identified as objects with low infrared excess in the spectral energy distribution (SED). However, it is difficult to classify transitional disks only with SED.

In this study, I reported the results of high-resolution (0.14 arcsec) Atacama Large Millimeter/submillimeter Array (ALMA) observations of the 225 GHz dust continuum and CO molecular emission lines from the transitional disk around SY Cha (distance: 180.7 pc, mass: $0.78 M_{\odot}$, age: 3 million years). Our high-resolution observations clearly revealed the inner cavity and the central point source for the first time. The radial profile of the ring can be approximated by a ~ 35 au radius bright and narrow inner ring superimposed on a ~ 140 au radius fainter outer ring. The lower limit of the total dust mass is estimated to be $1.2 \times 10^{-4} M_{\odot}$. Furthermore, I found that there is a weak asymmetry in dust continuum emission by the visibility analysis.

For gas emissions, I detected $^{12}\text{CO}(2-1)$, $^{13}\text{CO}(2-1)$ and $\text{C}^{18}\text{O}(2-1)$, from which I estimated the total gas mass of the disk to be $2.6 \times 10^{-4} M_{\odot}$, assuming a CO/H₂ ratio of 10^{-4} . This result shows that the total gas mass is comparable with that of dust; however, the estimated gas value may be increased by a factor of 10–100 by CO depletion. The observations showed that the gas is present inside the dust cavity. The analysis of the velocity structure of the $^{12}\text{CO}(2-1)$ emission line revealed that the velocity is distorted at the location of the dust inner disk, which may be owing to warping of the disk or radial gas flow within the cavity of the dust disk.

High-resolution observations of SY Cha showed that this system is composed of a ring and a distorted inner disk, which may be common, as indicated by the survey of transitional disk systems at a resolution of ~ 0.1 arcsec.

概要

遷移円盤とは中心領域のダスト放射が弱い空隙状の構造を持つ円盤であり、進化の進んだ原始惑星系円盤と考えられているが、その形成メカニズムは分かっていない。遷移円盤はスペクトルエネルギー分布（SED）において、赤外超過が少ない天体として同定される。しかし、ALMA 望遠鏡による多種多様な円盤構造の高空間分解能観測がなされ、遷移円盤最内域の詳細構造の理解は SED のみでは困難であることが明らかになってきた。

本研究では ALMA 望遠鏡を用いた遷移円盤サーベイの選出天体の 1 つである SY Cha（距離：180.7 pc, 質量： $0.78M_{\odot}$, 年齢：300 万年）の 225GHz ダスト連続波と CO 分子輝線の高空間分解能データ（0.14 秒角）の解析を行った。ダスト連続波からは、半径およそ 100au のリング構造に加え、SED から判別できなかった中心点源が検出された。低解像度での撮像は過去に ALMA でなされていたが、中心部の空隙と中心点源がはっきりとイメージ上で確認されたのは初めてである。これに加え、マルコフ連鎖モンテカルロ法（MCMC）を用いて、ダスト連続波のビジビリティを軸対称な円盤モデルでフィッティングした結果、観測された円盤は幅 ~ 140 au のリング（動径方向の放射強度分布がガウシアン）と幅 ~ 35 au のリングの足し合わせで構成されたモデルで十分説明できることが分かった。ここで得られた軸対称モデルをデータから差し引くと、最大で 15% 程度の引き残りが確認され、ダストリングの明るさの非軸対称性が明らかになった。

今回の観測では $^{12}\text{CO}(2-1)$, $^{13}\text{CO}(2-1)$, $\text{C}^{18}\text{O}(2-1)$ も検出され、光学的に薄い $^{13}\text{CO}(2-1)$ においてはダスト連続波と似たリング状の構造が見られた。また、温度を $^{12}\text{CO}(2-1)$ から求めたピーク輝度温度、CO/H₂ 存在比を 10^{-4} と仮定して、 $^{13}\text{CO}(2-1)$ から見積もられるガス総質量はダスト総質量と同程度であることが示唆された。しかし、SY Cha が属する星形成領域では CO の枯渇が報告されており、推定値よりも 10–100 倍大きい可能性がある。

$^{12}\text{CO}(2-1)$ 輝線の速度構造の解析からは円盤の中心付近で速度場の歪みが確認された。この原因として、動径方向の高速な流れ、または動径方向で円盤の回転軸が変化する構造が考えられる。このうち後者は warp 構造と呼ばれ、先行研究では内部円盤の傾きにより中心星からの放射を遮り、外部円盤に影を作る効果が提案されている。内部円盤の傾きによって中心星の照射を遮ることでダストリングの明るさの非軸対称性を説明できる可能性があることがわかった。本論文では、以上の結果を報告するとともに、円盤構造について議論した。

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Chapter 1

Introduction

1.1 Overview of Protoplanetary disk

When materials infall in molecular cloud under its own gravity, disks are formed around protostars by angular-momentum conservation during star formation. The circumstellar disk is composed of gas and dust surrounding young stars and is the birthplace of planets, and thus it is called “protoplanetary disk”. The protoplanetary disk coevolves with the central star and eventually disperses. After the formation of a planet, the gravitational interaction between the disk and planet is expected to excite various structures in the disk. Figure 1.1 shows a schematic view of the star and disk formation process. The four different stages (class 0–III) are identified from the observed infrared excess relative to a blackbody spectrum (Dauphas & Chaussidon 2011). Class 0 sources emit strongly at mm wavelengths, but lack both optical and infrared emission in their SEDs. This suggest that the thick envelope around it will hide the hot core from view in the SED. Class I sources exhibit large near-infrared excesses and peak in far-infrared in their SED. Once a disk forms, the luminosity from the central star heats up the inner disk, which emits in the near-infrared. While a less dense outer envelope absorbs most of stellar light, it re-radiates at longer wavelengths. Class II sources are identified by the flat or declining infrared slopes in their SEDs. When the envelope has dispersed, a star and its protoplanetary disk remain. The mass accretes from the disk to the star, and the stellar radiation will be the main heating source to the disk. Class III sources are shown little signs of excess emission at infrared wavelengths in their SEDs. After the disk has disappeared, a star and its planetary system remain. Planets are too faint to be detected in the SED, but smaller bodies may collide and generate a dust disk that can re-emit a small portion of the stellar light. Recently, many examples of complex structures in protoplanetary disks have been identified by Atacama large millimeter/submillimeter array (ALMA) observations (e.g., Fukagawa et al. 2013; van der Marel et al. 2013; ALMA Partnership 2015; Andrews et al. 2016). Among them, disks with less dust close to the central star are called transitional

disks. It is believed that the transitional disks are evolved protoplanetary disks; however, there are also some signs that these disks pass through a separate evolutionary process (Pinilla et al. 2018). Transitional disks were originally identified as young stellar objects (YSOs) with few near-IR excesses ($1\text{--}5\ \mu\text{m}$), but with significant excesses at mid-IR ($5\text{--}20\ \mu\text{m}$) and far-IR wavelengths in their spectral energy distributions (SEDs) (Calvet et al. 2002; Calvet et al. 2005).

Recent ALMA high-resolution observations have obtained an inner ring with a radius of ~ 4 au in the disk around DM Tau, which has been classified as a transitional disk object (Kudo et al. 2018). This result shows that whether there is an additional component in the central gap of a transitional disk cannot be judged solely from its SED. Moreover, in Francis & van der Marel (2020), ALMA archival continuum data of 38 transitional disks with resolved dust cavities shown in figure 1.2 have suggested that at least 18 of transitional disks in their sample host an inner dust disk. From the comparison between ALMA data and SEDs, the near-infrared excess in a transitional disk may be uncorrelated with the mass of mm-size dust in the inner disk. Thus, high-resolution observations that reveal the actual distributions of gas and dust at a small scale are necessary for better understanding of the transitional disks.

1.2 The aims of this Study

In this thesis, I report the results of high-resolution ALMA observations of the disk around SY Cha. SY Cha is a T Tauri star with the mass of $0.78\ M_{\odot}$ (Manara et al. 2017). The stellar age is estimated to be ~ 3 Myr (Siess et al. 1997; Siess et al. 2000), and it exhibits a mass accretion rate of $\dot{M}_{\star} = 3.89 \times 10^{-10}\ M_{\odot}/\text{yr}$ (Manara et al. 2017). Other properties are summarized in table 1.1. The SED of SY Cha (figure 1.3) does not show a significant excess in the near-infrared region. However, for the first time, our high-sensitive and high-spatial resolution observations of the circumstellar environment revealed the presence of an inner disk around SY Cha.

The remainder of this thesis is structured as follows. I present the observational setup and data reduction in chapter 2, and then I report the analysis results in chapter 3. In chapter 4, I discuss the causes of the velocity distortion detected by our observations. Finally, I present conclusions in chapter 5.

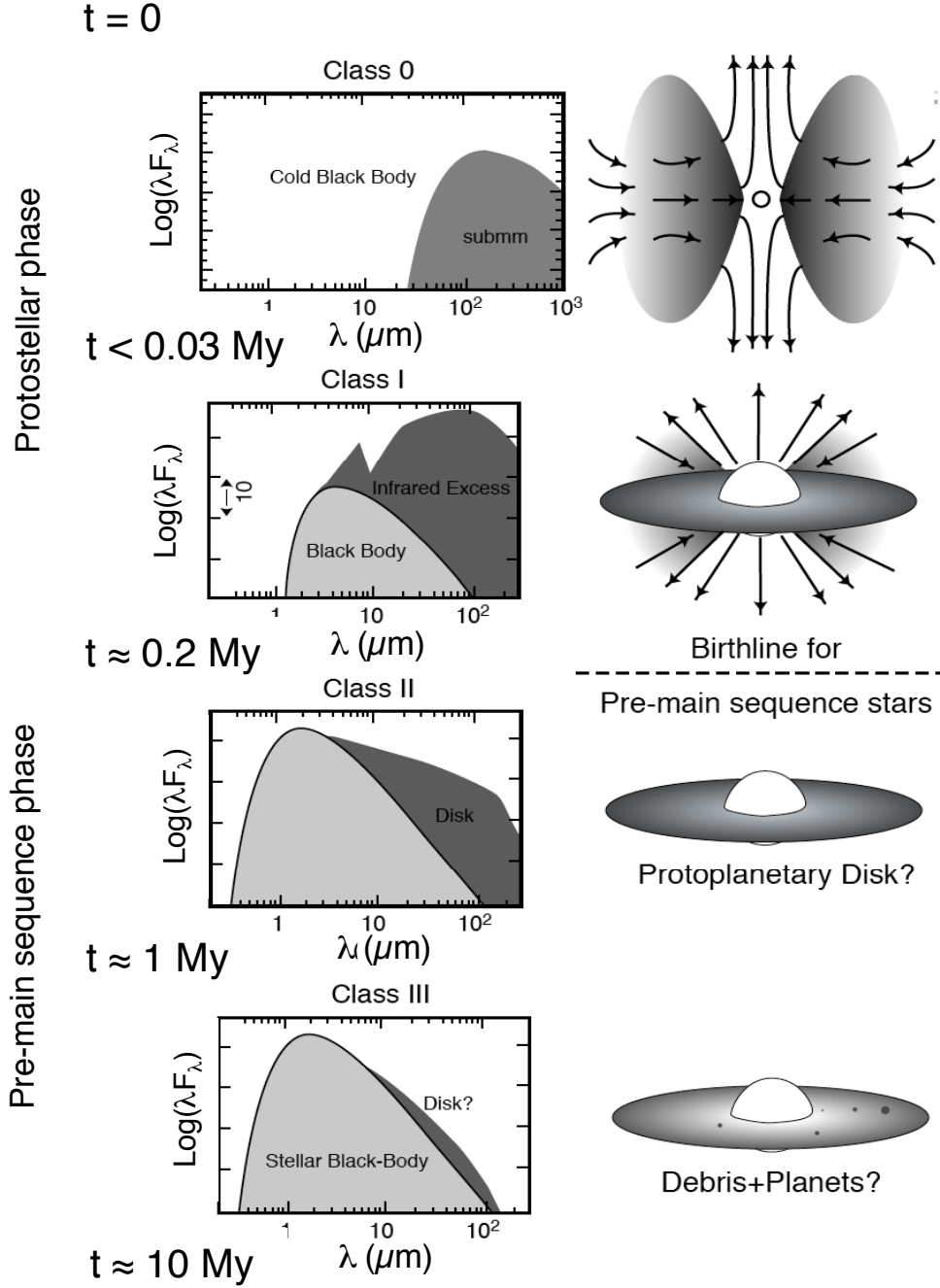


Figure 1.1: Schematic view of the common evolutionary phases of a forming star (Dauphas & Chaussidon 2011). The left panels show the SED with the star in light gray and the envelope/disk material in dark gray, while corresponding illustrations of the disks are shown on the right. Class 0/I sources quickly evolve to pre-main sequence stars known as Class II sources, which are surrounded by protoplanetary disks. In the final stages of disk evolution, debris disks around Class III sources exhibit little excess at long wavelengths.

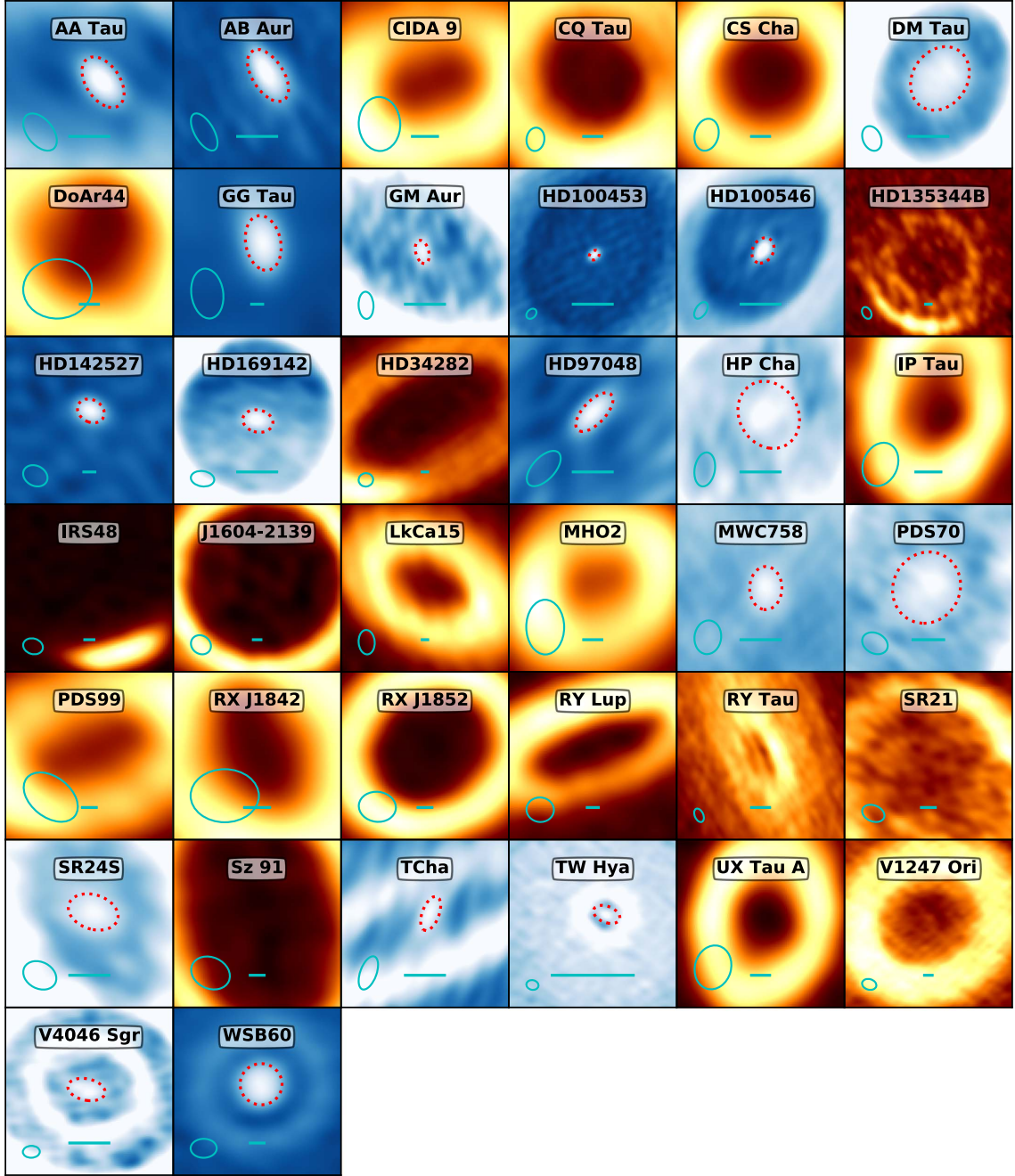


Figure 1.2: ALMA image continuum gallery of the zoom-up transitional disks (Francis & van der Marel 2020). In images where I have detected an inner disk, a blue colormap with the brightest region set to the peak flux of the inner disk is used, and the red dotted line indicates the FWHM of the Gaussian fit. The beam size is shown in the bottom left and the scalebar at the bottom is 10 au in length.

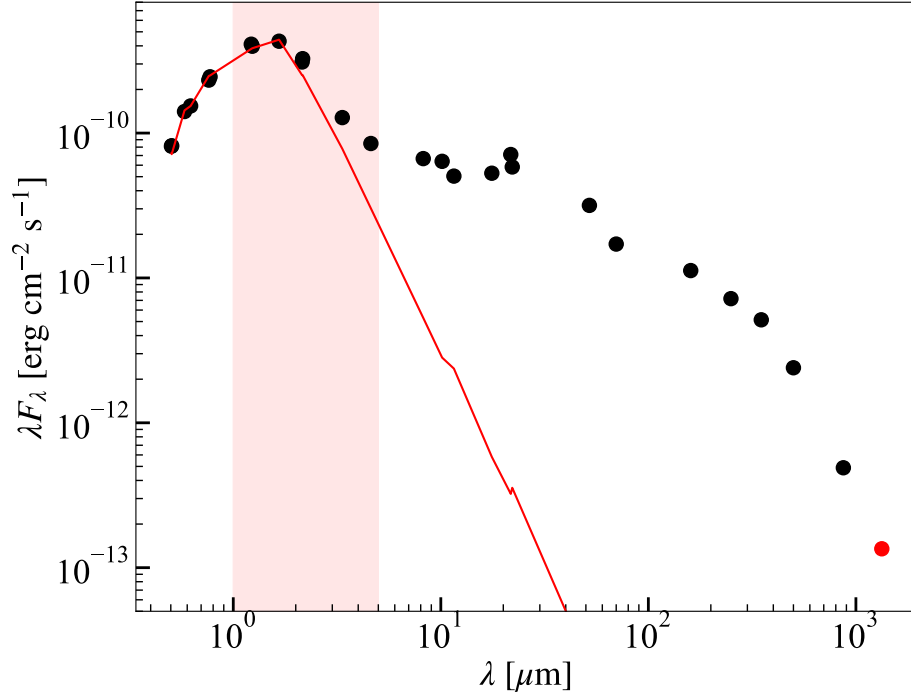


Figure 1.3: Spectral energy distribution (SED) of SY Cha (Fouqué et al. 2000; Cutri et al. 2003; Wright et al. 2010; Ishihara et al. 2010; Neugebauer et al. 1984; Winston et al. 2012; Belloche et al. 2011). The red line indicates the photospheric emission estimated by VOSA (Bayo et al. 2008). The red circle is the flux information obtained by our observation. The red filled area indicate near-IR wavelengths (1–5 μm).

Table 1.1: Properties of SY Cha

Parameter	Value
Stellar Mass $M_{\star}$	$0.78 M_{\odot}$ (Manara et al. 2017)
Mass accretion rate $\dot{M}_{\star}$	$3.89 \times 10^{-10} M_{\odot}/\text{yr}$ (Manara et al. 2017)
Stellar Age	3 Myr (Siess et al. 1997; Siess et al. 2000)
Stellar Radius $R_{\star}$	$1.58 R_{\odot}$ (Gaia Collaboration et al. 2018)
Stellar Limunosity $L_{\star}$	$0.465 L_{\odot}$ (Gaia Collaboration et al. 2018)
Effective Temperature T_{eff}	3792 K (Gaia Collaboration et al. 2018)
Distance d	180.7 pc (Gaia Collaboration et al. 2021)
Spectral type	K5Ve (Frasca et al. 2015)
Proper Motion $\Delta\text{Ra.}$	-23.738 mas/yr (Gaia Collaboration et al. 2021)
Proper Motion $\Delta\text{Dec.}$	2.804 mas/yr (Gaia Collaboration et al. 2021)

Chapter 2

Observations and Data Reduction

SY Cha was observed with ALMA in Band 6 during Cycle 6 (2018.1.00689S, PI: Muto). The observations were conducted using an extended configuration (EC) on June 22, 2019, and by compact configuration (CC) on August 19 and September 25, 2019, with the spectral windows (SPW) covering $^{12}\text{CO}(2-1)$, $^{13}\text{CO}(2-1)$, $\text{C}^{18}\text{O}(2-1)$ and continuum emission, as summarized in tables [2.1](#) and [2.2](#).

The visibility data were reduced and calibrated using the Common Astronomy Software Applications (CASA) package [McMullin et al. \(2007\)](#). I used the CASA pipeline (EC data: CASA 5.40-70 42254M, CC data: CASA 5.6.1-8 42866M) to calibrate the data, as well as to flag bad data.

Two spectral windows for continuum observations with a bandwidth of 2 GHz (table [2.2](#)) were combined and averaged to obtain continuum data centered at 225 GHz. The continuum image was reconstructed by Multi-Scale CLEAN ([Cornwell 2008](#)) of CASA (version 5.7.2-4) with natural weighting and `scales parameters` of [0, ‘beam size’, ‘2×beam size’].

I performed self-calibration in phase for CC visibility using a model of the disk around SY Cha created by the `tclean` task in the CASA tools, after correcting the position offset owing to the proper motion between CC data 1 (observation date: August 19) and CC data 2 (observation date: September 25) by `fixvis` and `fixplanets` tasks in the CASA tools. The self-calibration in both phase and amplitude was then run with `combine` “obs, scan” and `solint` “inf” for the CC visibility calibrated in phase, but this process produced almost no change in the resultant image. Thereafter, I concatenated the CC and EC data to produce a high resolution image. The absolute position information in the CC data was lost in self-calibration processes, but I could align the two datasets by using the fact that the disk is almost axisymmetric (see chapter 3). The phase centers of the CC and EC data were set at the position where the root mean square (RMS) of the imaginary part of the visibility was minimized, that is, the phase centers of each dataset were chosen where the asymmetry of each image was minimized. The final round of self-calibration in

phase was then performed with `combine` “obs, scan” and `solint` “inf” for concatenated visibility. This corrects for the slight difference of the phase center between observations. I applied a Gaussian taper with an FWHM of $1.5\text{ M}\lambda$ to improve the signal-to-noise ratio by about a factor 2.5 while maintaining the beam sufficiently sharp. Finally, I obtained a dust continuum image with a beam size of $0.145'' \times 0.109''$ and an RMS noise of $17.5\text{ }\mu\text{Jy/beam}$.

All line data were extracted by subtracting the continuum in the visibility domain with the task `uvcontsub` in the CASA tools. Before imaging the line emission, the solution tables obtained from the self-calibration of the continuum data were applied to the line data. Channel maps with the velocity width of 0.7 km/s were created by Multi-Scale CLEAN in a velocity range of $V_{\text{LSRK}} = -4.3\text{--}12.5\text{ km/s}$. Subsequently, I set the density weight and scale parameters similar to the continuum imaging. Because $^{12}\text{CO}(2\text{--}1)$ emission was detected in the EC data, I performed imaging using the concatenated visibility. The beam size and RMS noise of each channel map are presented in table 2.3. The beam size of the highest-resolution image is $0.145'' \times 0.110''$.

I created the moment maps from each channel map using the `bettermoments` package (Teague & Foreman-Mackey 2018). Here, the channel maps were applied to the Keplerian mask generated with the `keplerian_mask` package (Teague 2020) before creating the moment map. This package can calculate masks based on the expected emitting surface of a Keplerian disk. The calculation considered stellar mass, distance to the star, systemic velocity, position angle (PA), and inclination obtained from observations. In addition, I assumed the height of the emitting surface relative to the radius to be 0.2 that is a little higher than the pressure scale height (see chapter 3.3.1). The mask was convolved with a 2D Gaussian that has the same size as the synthesized beam of each channel map. When creating moment 1 and 2 maps, the clipping levels were set to 3σ (1σ is the RMS of each channel map).

Table 2.1: Observational Setup

	EC data	CC data 1	CC data 2
Obs. Date	22 June 2019	19 August 2019	25 September 2019
Configuration	C43-9	C43-7	C43-6
Number of Antenna	48	45	50
Max. Baseline [km]	16.2	3.6	2.6
Min. Baseline [m]	83.1	41.4	15.1
On-source Time [min]	72.75	15.25	15.25
Calibrators	J1107-4449 ^{1,2,3,4}		
	J1617-5848 ^{1,2,3,4}	J1107-4449 ^{1,2,3,4}	J0635-7516 ^{1,2,3,4}
	J1145-6954 ⁴	J1058-8003 ^{4,5}	J1058-8003 ⁵
	J1148-7819 ⁵	J1155-8101 ⁶	J1155-8101 ⁶
	J1155-8101 ⁶		
CASA pipeline version	42254M	42866M	42866M

¹Absolute flux calibrator, ²Atmosphere calibrator, ³Bandpass calibrator,

⁴Pointing calibrator, ⁵Complex gain calibrator, ⁶Check source

Table 2.2: Correlator Setup

	Continuum ¹	¹² CO(2–1)	¹³ CO(2–1)	C ¹⁸ O(2–1)
Central Frequency [GHz]	216.984, 232.983	230.521	220.383	219.544
Number of Channel	128, 128	3840	1920	1920
Band Width [GHz]	2, 2	0.94	0.47	0.47
Velocity width [km/s]	21.6, 20.1	0.317	0.332	0.333
Rest Frequency [GHz]	-	230.538	220.399	219.560

¹ (Lower sideband, Upper sideband)

Table 2.3: Imaging Parameters

	Continuum	¹² CO CC only	¹² CO concat	¹³ CO	C ¹⁸ O
Channel Width [km/s]	5330	0.7	0.7	0.7	0.7
Number of Channel	1	25	25	25	25
Density Weighting	natural	natural	natural	natural	natural
Gaussian taper	1.5 M λ	-	1.5 M λ	-	-
Beam size	0.145'' $\times$ 0.109''	0.328'' $\times$ 0.259''	0.145'' $\times$ 0.110''	0.343'' $\times$ 0.262''	0.344'' $\times$ 0.263''
Beam Position Angle	12.7°	-44.4°	13.7°	-44.0°	-43.5°
RMS Noise [mJy/beam]	0.0175	2.19	1.37	2.19	1.81
Peak Channel [km/s]	-	2.0	1.3	6.2	6.2
Peak Intensity [mJy/beam]	1.33	96.0	24.7	39.1	15.4
SNR	76	44	18	18	8.5
Total Flux Density [mJy]	56.7	-	-	-	-
Integrated Flux Density [Jy $\cdot$ km/s]	-	6.5	9.9	1.6	0.3

Chapter 3

Data Analysis and Results

3.1 Synthesized images

3.1.1 225GHz Dust Continuum

The dust continuum image obtained by MS-CLEAN is shown in figure 3.1. The emission consists of a ring and a central source of 0.45 mJy. The continuum emission has a total flux density of 56.7 mJy that was measured above 3σ in the emission.

To characterize the ring structure, I performed ellipse fitting to the local maxima of the radial profile of the surface brightness for every 15° in PA (figure 3.1(b)), as explained in appendix F. The center of the best-fit ellipse was found to be at the same position as the central source. The major axis of the ellipse is along the direction of $PA = -15.3(\pm 1.7)^\circ$, and the aspect ratio is $0.62(\pm 0.016)$, corresponding to $51.7(\pm 1.17)^\circ$ in inclination angle if the emission originates from an intrinsically axisymmetric and geometrically thin structure. PA and inclination reported by Pinilla et al. (2018) (SY Cha is introduced as J10563044) were -20° and 39° , respectively. I obtained better estimate of the disk inclination by the high-resolution observation.

The surface brightness profiles along the major and minor axes are presented in figure 3.2. I fit these profiles with three Gaussian components. Two of them correspond to the ring, and the remaining corresponds to the central emission. The results of the Gaussian fitting along the major and minor axes are shown in tables 3.1 and 3.2, respectively.

The locations of the peaks r_{peak} were almost symmetric to the central emission. The ring width is twice as large as the size of the synthesized beam ($0.145'' \times 0.109''$, 12.7°), while the FWHM of the central emission is close to that of the beam. Therefore, I consider that the width of the outer ring is marginally resolved, whereas the central source is unresolved. Note that even with the image made using EC data only (figure E.1(a) of appendix E), the central source is unresolved. As shown in table 3.3, the synthesized beam of the image made using EC data only is ~ 40 mas (~ 7 au) and can be regarded as

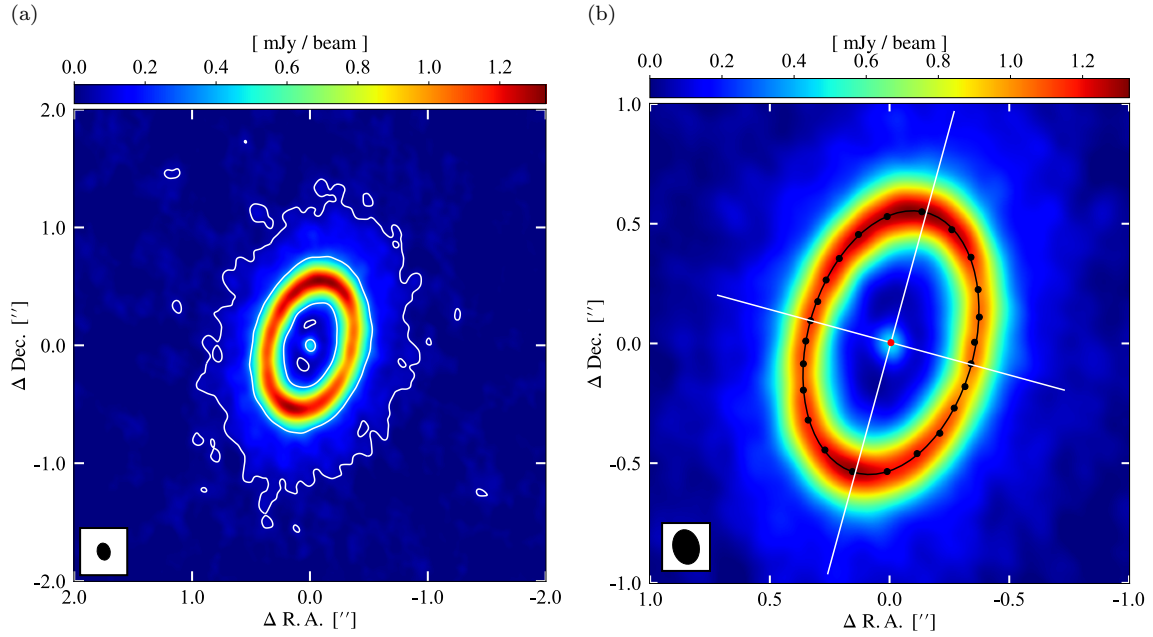


Figure 3.1: 225 GHz dust continuum image around SY Cha. The synthesized beam size ($0.145'' \times 0.109''$) is shown at the bottom left. (a) Overview of disk. The white contour denotes the 3σ , 20σ , where the 1σ level is the RMS noise ($= 17.5 \mu\text{Jy beam}^{-1}$). (b) Results of ellipse fitting are indicated by the black line. The black points are the peak points of the radial profile of the surface brightness every 15° in the position angle. The red point indicates the center of the best-fit ellipse. The white solid line denotes the major and minor axes of the ellipse.

the upper limit on the diameter size of the inner dust disk. I found that the radial profiles at the outer radii ($r \gtrsim 0.5$ arcsec) do not follow the Gaussian distribution, indicating that there is a weak emission that extends to ~ 1.5 arcsec from the central star. More detailed analyses of the brightness distribution of dust continuum emissions in the visibility domain are presented in chapter 3.2.

In the radial profile along the minor axis, the peak on the east-side is $\sim 10\%$ higher than that on the west-side. This difference corresponds to 5σ ($1\sigma = 17.5 \mu\text{Jy/beam}$); thus, it is statistically significant. The ring emission may be asymmetric along the minor axis, probably because the eastern side is the far side of the disk. The inner wall of the ring, which has slightly high temperature due to stellar irradiation, is observed in the eastern side (see chapter 4 for further discussion).

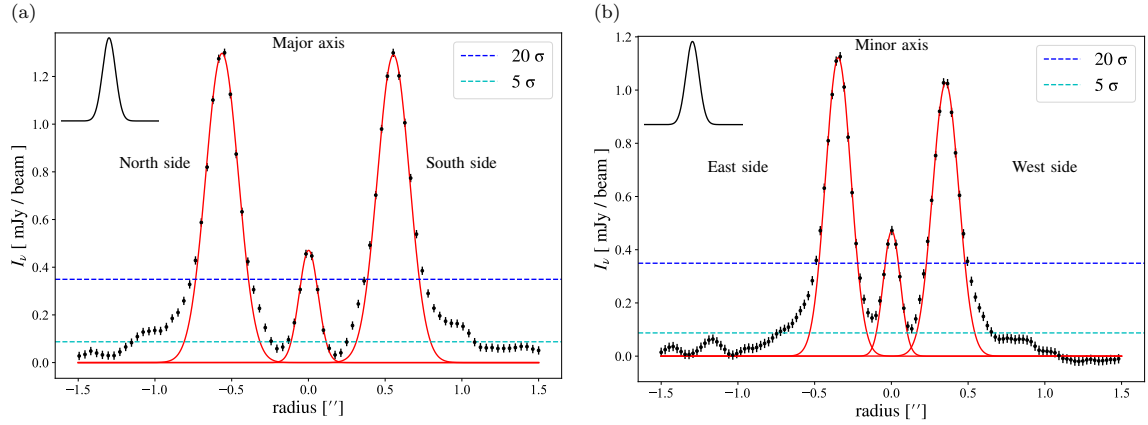


Figure 3.2: Radial profiles of the intensity along the (a) major and (b) minor axes (figure 3.1(b)). The red line shows the best-fit curve in the Gaussian fitting at each peak. The error bar indicates the RMS noise ($= 17.5 \mu\text{Jy beam}^{-1}$). The cyan and blue dashed line are 5σ and 20σ , respectively. The black curve in the top left indicates the profile of the synthesized beam.

Table 3.1: Results of gaussian fitting at the major axis

Parameter	North	inner	South
$r_{peak}[\text{arcsec, au}]$	-0.563, -102	0.001, 0	0.554, 100
FWHM[arcsec, au]	0.250, 45	0.148, 27	0.247, 45
$I_\nu[\text{mJy/beam}]$	1.295	0.470	1.289

Table 3.2: Results of gaussian fitting at the minor axis

Parameter	East	inner	West
$r_{peak}[\text{arcsec, au}]$	-0.346, -63	0.002, 0	0.354, 64
FWHM[arcsec, au]	0.195, 35	0.132, 24	0.202, 37
$I_\nu[\text{mJy/beam}]$	1.122	0.469	1.026

Table 3.3: Properties of each dust continuum image

	EC data	CC data
Beam size	0.043'', 0.024'' 17.8°	0.337'', 0.254'' -42.9°
rms [$\mu\text{Jy/beam}$]	13.6	26.7
Total Flux [mJy]	37.2	56.0

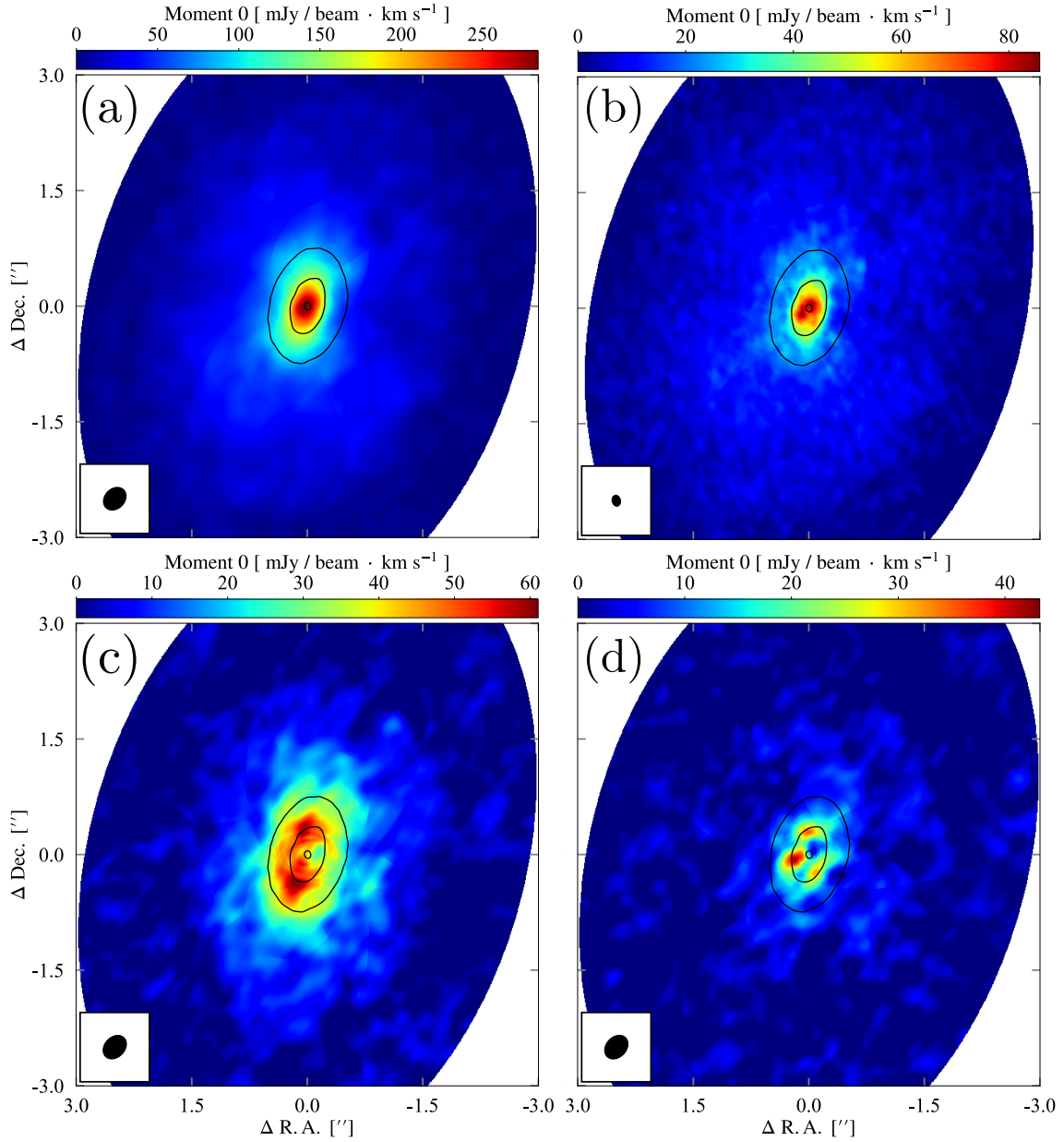


Figure 3.3: Moment 0 maps of (a) $^{12}\text{CO}(2-1)$ in CC data, (b) $^{12}\text{CO}(2-1)$ in concatenated data, (c) $^{13}\text{CO}(2-1)$ in CC data, (d) $\text{C}^{18}\text{O}(2-1)$ in CC data. The black ellipse at the bottom left of each panel represents the beam size. The contours in these maps indicate the 20σ level of the dust continuum, where $1\sigma = 17.5 \mu\text{Jy}/\text{beam}$.

3.1.2 CO Line

The moment 0 (integrated intensity) maps of the CO gas emissions are shown in figure [3.3](#). Each panel corresponds to ^{12}CO CC data, ^{12}CO concatenated data, ^{13}CO data, and C^{18}O

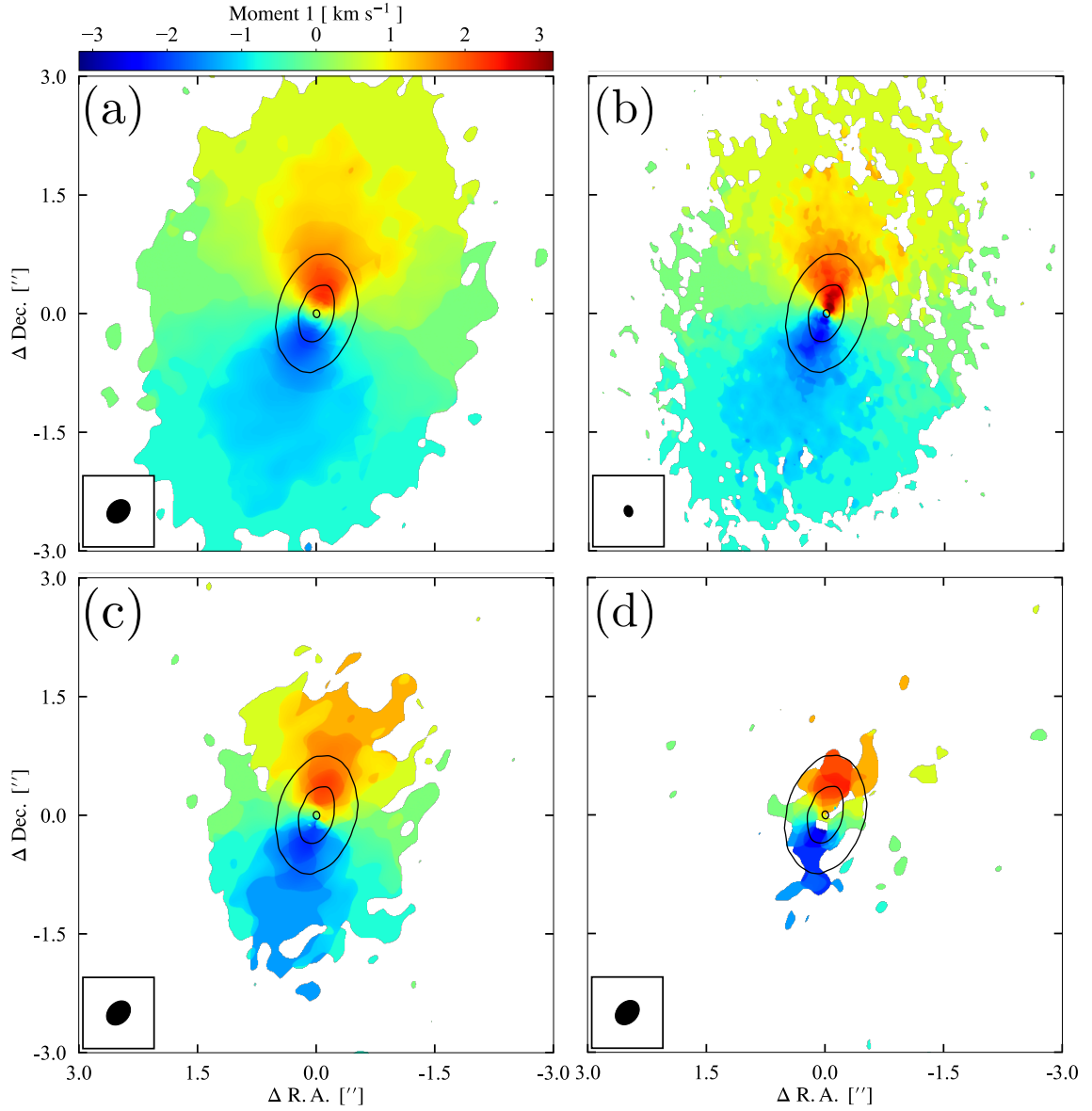


Figure 3.4: Moment1 maps of (a) $^{12}\text{CO}(2-1)$ in CC data, (b) $^{12}\text{CO}(2-1)$ in concatenated data, (c) $^{13}\text{CO}(2-1)$ in CC data, (d) $\text{C}^{18}\text{O}(2-1)$ in CC data. The black ellipse at the bottom left of each panel represents the beam size. These color bars show the velocities based on systemic velocity $V_{\text{LSRK}} = 4.1 \text{ km/s}$. The contours in these maps indicate the 20σ level of the dust continuum, where $1\sigma = 17.5 \mu\text{Jy/beam}$. When creating the moment 1 maps, the clipping levels were set in 3σ .

data. I summarized the integrated flux of each moment 0 map in table [2.3](#). The ^{12}CO line shows that the line emission comes from the elliptical region whose major axis well matches with that of the dust ring. Therefore, I consider that the ^{12}CO line emission is

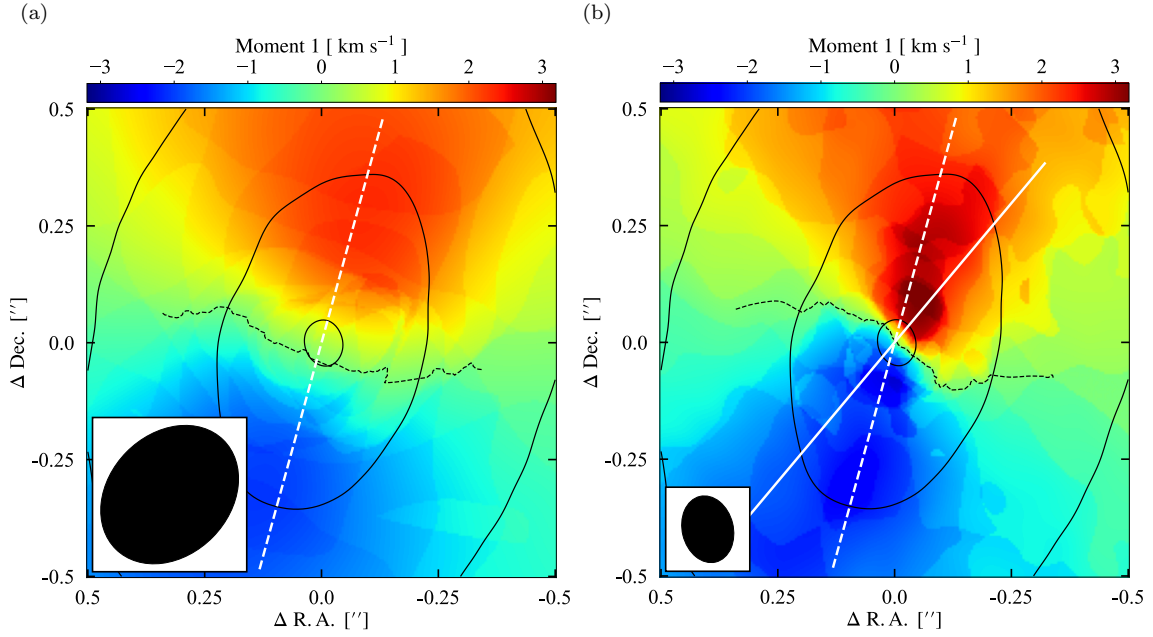


Figure 3.5: Zoom-up moment 1 map made from the $^{12}\text{CO}(2-1)$ emission. The black ellipse at the bottom-left of each panel represents the beam size. (a) Zoom-up image of the CC data. (b) Velocity distribution near the inner disk. The black dotted line indicates the systemic velocity. The solid lines denote the major and of the inner disk, where the minor axis is the direction along the dotted line at the location of the ones.

not affected by an envelope or foreground cloud. I observe the ^{12}CO emission inside the dust ring and it peaks at the location where the dust emission at the center of the ring is observed. Figure 3.4 shows the moment 1 (intensity-weighted velocity) map of ^{12}CO line. The velocity clearly shows the rotation pattern and the direction of large velocity gradient coincides with that of the major axis of the dust ring.

However, I see a peculiar velocity pattern in the vicinity of the central star. Figure 3.5 compares the moment 1 map of ^{12}CO emission near the central star obtained only by CC data (figure 3.5 (a)) and that by EC+CC data (figure 3.5 (b)). The low-resolution map reveals the velocity structure in the outer ring, whereas the high-resolution map clearly reveals the structure near the central star. While the line-of-sight velocity is almost zero along the minor axis of the dust continuum ring, as expected from the rotation in the disk-like structure (figure 3.5(a)), the velocity pattern inside the dust ring is distorted (figure 3.5(b)).

The moment 0 map of the ^{13}CO line emission also shows an extended distribution along the major axis of the dust ring. Contrary to the ^{12}CO emission, the ^{13}CO emission shows a ring-like structure, delineating the inner edge of the dust ring, and also shows an

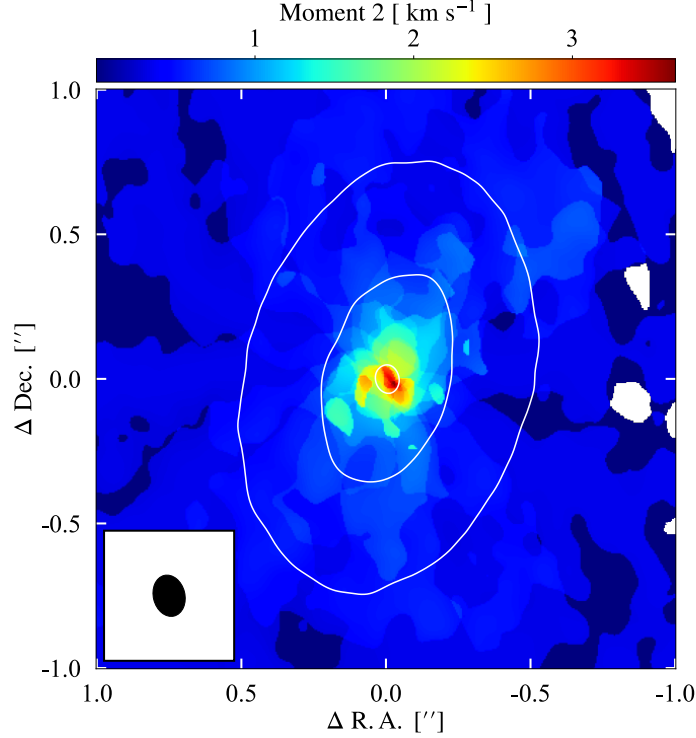


Figure 3.6: Moment 2 map of $^{12}\text{CO}(2-1)$ in the concatenated data. The synthesized beam size is shown at the bottom left. The contours in these maps indicate the 20σ level of the dust continuum, where $1\sigma = 17.5 \mu\text{Jy}/\text{beam}$.

east-west asymmetry, as in the case of the dust continuum. This is probably because the surface density of the gas is significantly low in the dust cavity, which is optically thin in the ^{13}CO line emission. The C^{18}O emission is weaker, but its distribution is ring-like with several patchy components, similar to the ^{13}CO emission. The velocity structure revealed in the moment 1 maps of both ^{13}CO and C^{18}O agree with that of ^{12}CO , which is consistent with rotation in a disk. In addition, the moment 2 (velocity dispersion) map shown in figure 3.6 indicates that the central star and the dust point source are at the same position. This is because the position at the star is expected to have the highest velocity dispersion. Moreover, the velocity dispersion along the minor axis of the disk is observed, which corresponds to the velocity distortion, as shown in figure 3.4(b).

Figure 3.7(a) shows the position-velocity diagram (PV-diagram) of ^{12}CO emission along the major axis of the ring. Assuming a stellar mass of $0.78M_{\odot}$ (Manara et al. 2017) and a disk inclination of 51.7° , as derived from the ellipse fitting to the continuum emission (chapter 3.1.1), the Keplerian rotation curves are shown by red curves in figure 3.7(a). The velocity field of the ^{12}CO emission is almost consistent with the Keplerian motion of the gas. However, there is another velocity gradient in the PV-diagram along the minor

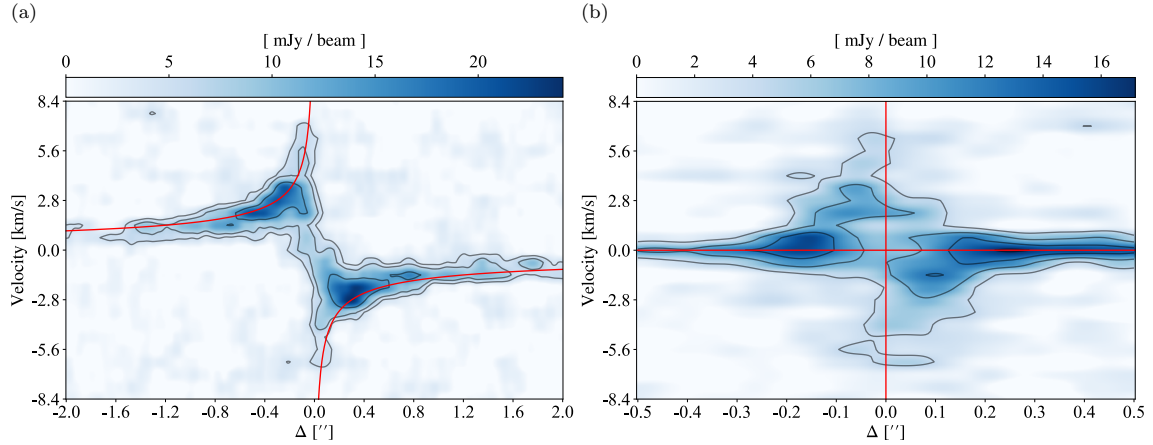


Figure 3.7: PV-diagram made from the $^{12}\text{CO}(2-1)$ cube along the (a) major and (b) minor axes of the outer ring. Contours are shown at $[3,5,10]\sigma$, where the 1σ level is 1.37 mJy/beam. (a): The red curves show the Keplerian velocity curve for the central star of $0.78 M_{\odot}$, and an outer disk inclination of 51.7° . (b): The solid red lines denote the center position, and the systemic velocity of 0. There exist velocity gradient in the vicinity of the center.

axis (figure 3.7(b)) that cannot be accounted for by the pure Keplerian motion in the disk, and there are high velocity components with the velocity shift of 2–7 km/s from the systemic velocity in the vicinity (<0.1 arcsec) of the central star. The distortion of the velocity pattern observed in moment 1 map may be caused by the warp (Casassus et al. 2015; Mayama et al. 2018) of the inner disk or fast radial flow (Rosenfeld et al. 2014). I discuss the nature of the velocity pattern in detail in chapter 4.

As shown in figures G.1–G.4 of appendix G, I obtained the channel maps of each CO isotopologue emission. ^{12}CO lines become optically thick and emit from the disk surface located above the disk mid-plane (figure 3.8). As shown in figure 3.9, the twin-line pattern is detected in the $^{12}\text{CO}(2-1)$ channel maps at $\Delta V = \pm 0.7$ km/s (see figure G.1), which can be interpreted as the emission tracing the upper and lower surfaces of the disk (de Gregorio-Monsalvo et al. 2013; Tsukagoshi et al. 2019). This pattern is expected to be identified in the region closer to us. The west-side shows the pattern more clearly in figures G.1–G.4. This is reasonable if the east-side corresponds to the far-side, as mentioned in subsection 3.1.1.

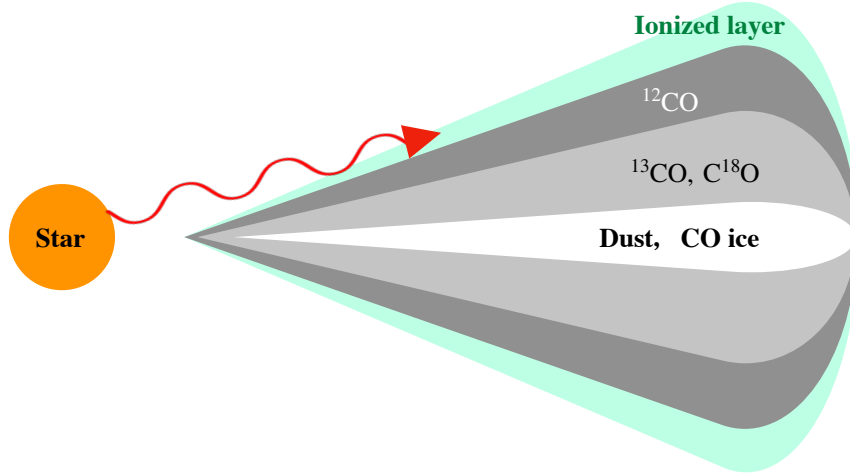
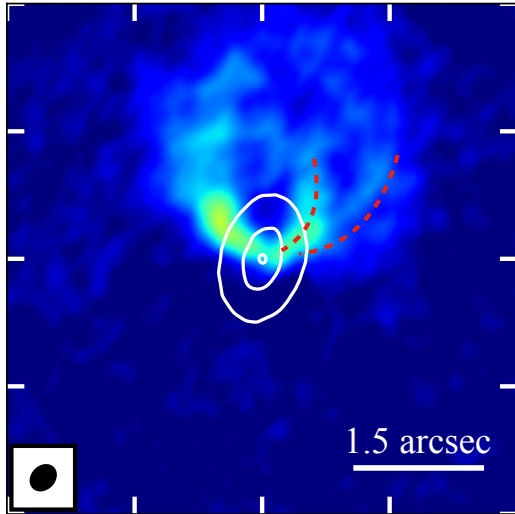


Figure 3.8: Schematic view of the various layers observed in the CO lines. The red wave arrow indicates a stellar light and means that the disk surface is hot by being directly irradiated with the light.

(a) 0.7 km/s ($V_{\text{LSRK}} = 4.8$ km/s)



(b)

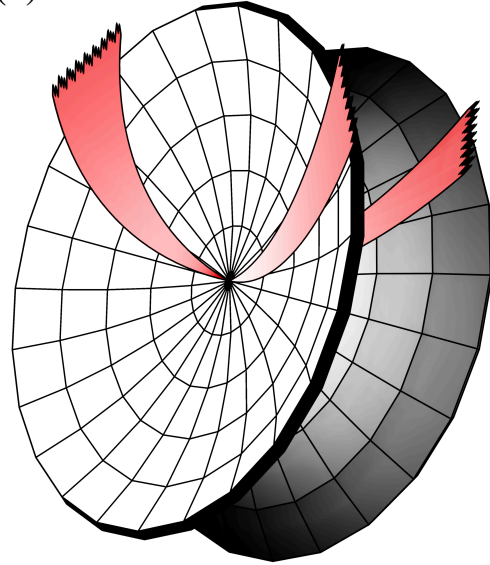


Figure 3.9: (a): $^{12}\text{CO}(2-1)$ line emission at velocity +0.7 km/s from the systemic velocity in the CC data. The emission from the disk produce the characteristic butterfly pattern. Moreover, the twin-line patterns traced by the red dashed lines were detected. (b): Schematic view of the inclined and flared disk shows the CO emission (red band) from two thin emitting surfaces (upper and lower) in a single channel. The emission from the upper surface of the disk is preferentially seen owing to the higher inclination with respect to the line of sight.

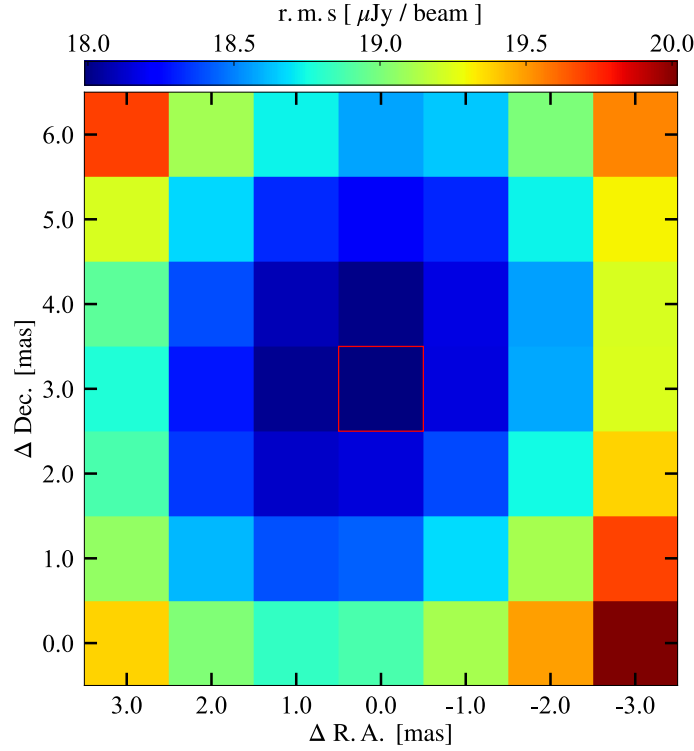


Figure 3.10: RMS of the images synthesized with only the imaginary part of the visibility by shifting 1 mas in R.A. and Dec directions. The axes show a shift from the phase center of the final-calibrated visibility. The RMS is calculated in the region with a radius of 2 arcsec. The phase center shifted by +3 mas in the Dec direction minimizes the RMS of the visibility imaginary (red box).

3.2 Analysis of dust continuum emission in visibility domain

In this section, I investigate the asymmetry of the dust emission rings in the visibility domain. The procedure is as follows. First, I removed the emission corresponding to the unresolved inner disk at the center of the image by subtracting 0.45 mJy from the real part of all the observed visibility. Secondly, I searched for the center of the ring structure. This is performed in the visibility domain by shifting the phase center and minimizing the imaginary part of the concatenated visibility. The real and imaginary parts of the visibility correspond to the symmetric and asymmetric components of the image with respect to 180° rotation, respectively. Because the observed ring structure is nearly axisymmetric, this procedure may be appropriate for defining the center of the ring (Kanagawa et al. 2021). When I concatenated the CC and EC data, I aligned the two images by minimizing the imaginary part of the visibility of each dataset (see chapter 2). However, because I performed the final round of self-calibration after concatenating each image, the phase

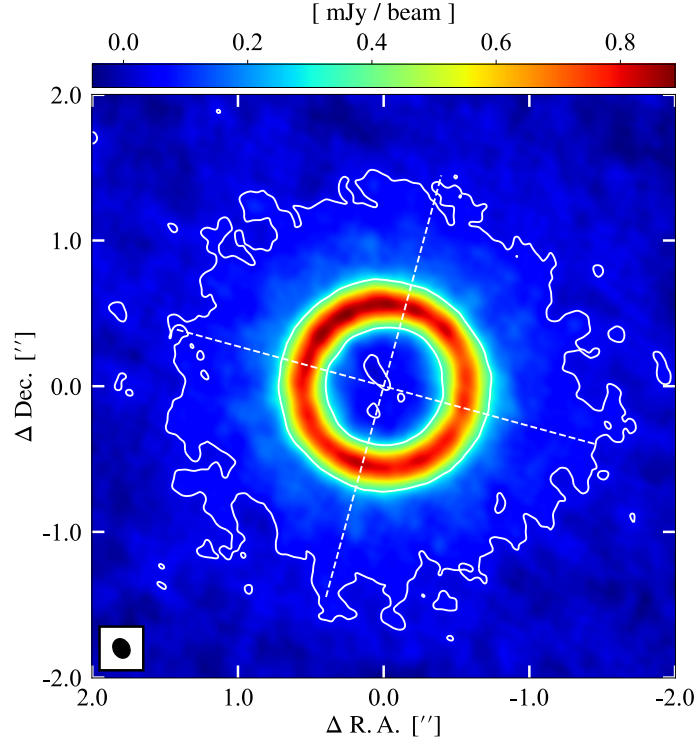


Figure 3.11: Image synthesized with the deprojected visibility. The synthesized beam ($0.140'' \times 0.113''$) is shown at the bottom left. The white contours denote the 3σ , 20σ level, where the 1σ level is the RMS noise ($= 16.2 \mu\text{Jy/beam}$).

center may be dislocated from the point where the imaginary part of the visibility is at a minimum. Thus, I applied this step again to the final image. Figure 3.10 shows the RMS level in each map that is synthesized with only the imaginary part as a function of the shift of phase center. The RMS of the images synthesized with only the imaginary part of the visibility were measured in the central region with a radius of 2 arcsec. The minimum value of RMS was obtained for the phase center shift $\Delta\text{R.A.} = 0 \text{ mas}$ and $\Delta\text{Dec.} = 3 \text{ mas}$. Finally, I deprojected the visibilities using the PA and inclination estimated by ellipse fitting. Figure 3.11 shows the image created from the deprojected visibilities.

The Fourier transform of the azimuthally symmetric distribution becomes a Hankel transform (Baddour 2009)

$$V_{\text{real}}(u) = 2\pi \int_0^\infty I(r) J_0(2\pi ur) r dr, \quad (3.1)$$

where $V_{\text{real}}(u)$, $I(r)$, and J_0 are the visibility real part of the deprojected uv-distance u , intensity of the distance from the center r , and zeroth-order Bessel function of the first type, respectively.

To fit the bright ridge of the ring as well as the extended periphery, I adopted a function

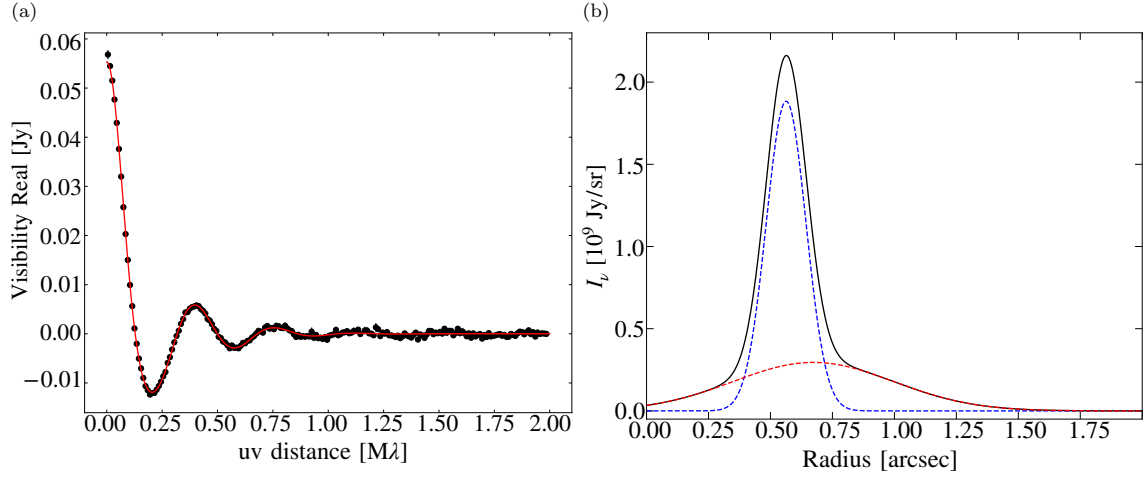


Figure 3.12: (a) Real part of the deprojected visibility for the observations (black dots) and best-fit model (red curve). (b) Radial profile of intensity as Fourier transform of the best-fit visibility (black line). The model consisted of two Gaussian ring components (blue and red dashed lines).

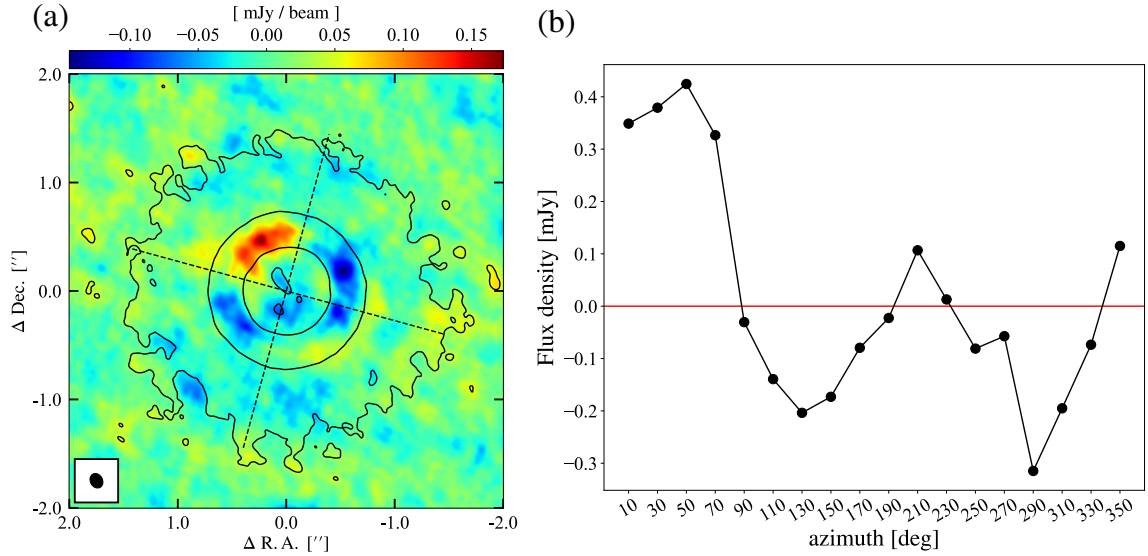


Figure 3.13: (a): Residual map obtained by subtracting the model visibility from the deprojected visibility. The synthesized beam ($0.140'' \times 0.113''$) is shown at the bottom left. The white contours denote the 3σ , 20σ , where the 1σ level is the RMS noise ($= 16.2 \mu\text{Jy beam}^{-1}$). From the figure, there is a quadrupole pattern of asymmetric intensity on the outer ring. (b): Azimuth profile of flux density measured in the range of $\Delta\text{P.A.} = 20^\circ$ and the radius of 0.3–1 arcsec in the residual map.

composed of two Gaussians as the model for radial brightness distribution, as follows:

$$I(r) = \sum_{i=1}^2 I_i \exp \left[-\frac{(r - r_{i,\text{peak}})^2}{2\sigma_i^2} \right], \quad (3.2)$$

$$I_i = F_i \left[2\pi \int_0^\infty \exp \left[-\frac{(r - r_{i,\text{peak}})^2}{2\sigma_i^2} \right] J_0(0) r dr \right]^{-1}, \quad (3.3)$$

where σ_i is related to the FWHM of the i -th ring by $\text{FWHM}_i = 2\sqrt{2\ln 2}\sigma_i$ and F_i is the total flux density of each ring. I find six parameters ($r_{1,\text{peak}}$, FWHM_1 , F_1 , $r_{2,\text{peak}}$, FWHM_2 , and F_2) that best fits the observed visibility profile using `emcee` (Foreman-Mackey et al. 2013). The best-fit parameters are summarized in table 3.4 and the visibility profile for the best-fit model is shown in figure 3.12(a). Figure 3.12(b) presents the radial brightness distribution expressed by Equation (3.2).

Table 3.4: Fitting parameters of two-gaussian model

Parameter	Value
$r_{1,\text{peak}}$ [arcsec, au]	0.563, 102
FWHM_1 [arcsec, au]	0.189, 34.0
F_1 [Jy]	0.032
$r_{2,\text{peak}}$ [arcsec, au]	0.674, 121
FWHM_2 [arcsec, au]	0.760, 139
F_2 [Jy]	0.024
reduced χ^2	1.61

Figure 3.13(a) shows the image subtracting the symmetric component from the original image. The residual asymmetric components may be characterized by a quadrupole pattern: positive residuals in the northeast and southwest to the star and negative residuals in the southeast and northwest. Figure 3.13(b) shows the azimuth profile of flux density measured in the range of $\Delta\text{PA} = 20^\circ$ and the radius of 0.3–1 arcsec in the residual map. This pattern shows east-west asymmetry, in which the east-side appears brighter than the west-side on the whole.

3.3 Physical Properties of the Disk

3.3.1 Dust Column Density

From the continuum emission, I estimated the optical depth and column density of dust in the SY Cha system. Here, I show simple estimates based on observed quantities because

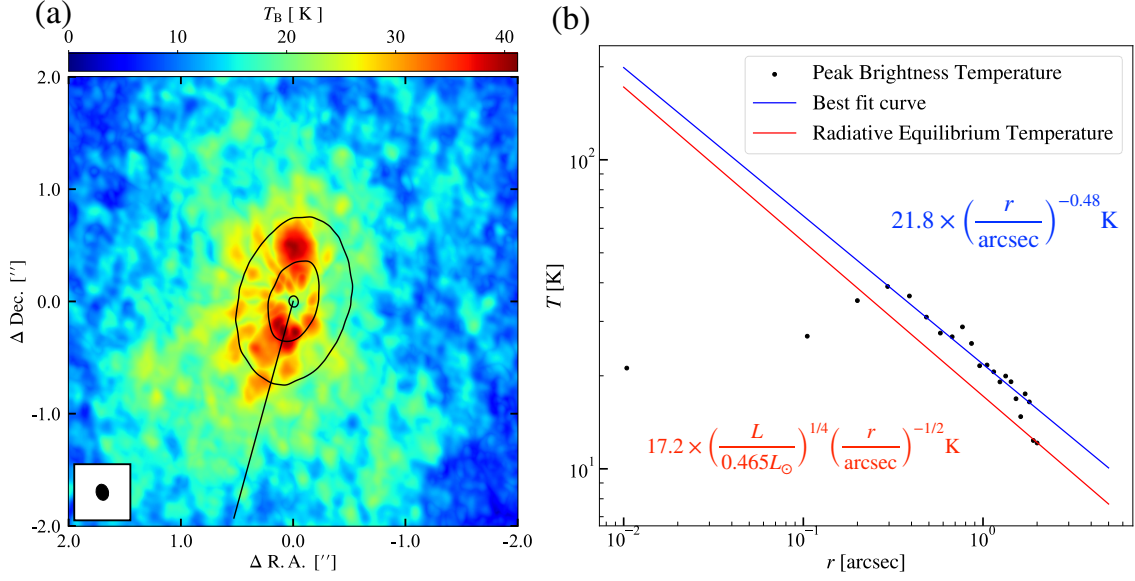


Figure 3.14: (a): Peak brightness temperature of $^{12}\text{CO}(2-1)$ emission. The synthesized beam size is shown at the bottom left. The contour indicates the 20σ level of the dust continuum, where $1\sigma = 17.5 \mu\text{Jy/beam}$. (b) Radial profile of the straight line in (a). The blue line indicates the curve fitted in area other than gray. The red line indicates the radiative equilibrium temperature of blackbody.

I only have Band 6 data. I estimate the optical depth of dust ring τ_d by

$$I_\nu = B_\nu(T)(1 - \exp(-\tau_d)), \quad (3.4)$$

where I_ν is the surface brightness of the continuum, and B_ν is the Planck function. As shown in figure 3.14, I adopt a temperature distribution derived from the power-law fit to the peak brightness temperature of the $^{12}\text{CO}(2-1)$, as

$$T = 264.12 \left(\frac{r}{\text{au}} \right)^{-0.48} \text{ K}. \quad (3.5)$$

This temperature is close to the radiative equilibrium temperature for a blackbody, $280(L/L_\odot)^{1/4}(r/\text{au})^{-1/2} \text{ K}$, which reads in the case of SY Cha,

$$T_{\text{rt}} = 231.22 \left(\frac{L}{0.465L_\odot} \right)^{1/4} \left(\frac{r}{\text{au}} \right)^{-1/2} \text{ K}, \quad (3.6)$$

where $0.465L_\odot$ is the luminosity of SY Cha (table 1.1). Assuming that the opacity of unit dust mass as

$$\kappa_d = 10 \left(\frac{\nu}{10^{12}\text{Hz}} \right)^\beta \text{ cm}^2 \text{ g}^{-1} \quad (3.7)$$

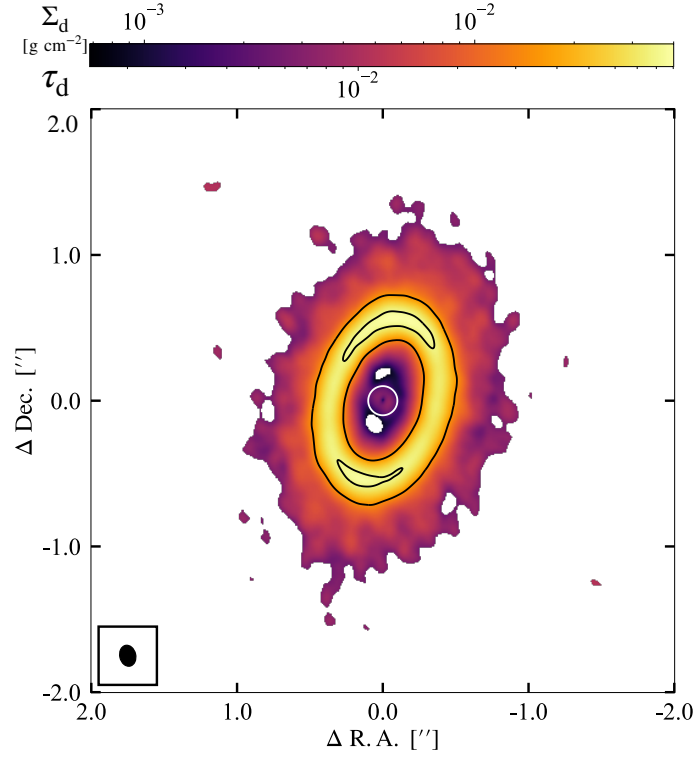


Figure 3.15: Optical depth τ_d and dust column density Σ_d . The black ellipse at the bottom-left shows the synthesized beam of the dust continuum image. The area where the emission is less than 3σ is indicated in figure 3.1(a) is masked, where $1\sigma = 17.5 \mu\text{Jy}/\text{beam}$. The black contours of the column density denote 0.015 g cm^{-2} and 0.035 g cm^{-2} . The white circle shows the calculation area of the mass of the inner dust disk.

(Beckwith et al. 1990), I estimated the dust column density $\Sigma_d (= \tau_d / \kappa_d)$. At 225 GHz, κ_d derived from Equation (3.7) is $2.25 \text{ cm}^2/\text{g}$ under the assumption that $\beta = 1$ (figure 3.15). The column density map is shown in figure 3.15, and the total dust mass integrated over the entire disk was estimated to be $\sim 1.2 \times 10^{-4} M_\odot$.

This value may be regarded as the lower limit of the total dust mass because the temperature near the disk mid-plane, where most of the dust particles are distributed, is expected to be lower than that in the upper layer of the disk traced by the ^{12}CO line emission (Chiang & Goldreich 1997). Furthermore, the brightness temperature of the dust emission (figure 3.16) gives the lower limit of the dust temperature, but it can underestimate the brightness temperature due to beam dilution effects in addition to the dust scattering. The dust scattering can depend on the dust compositions (Tazaki et al. 2016) and make the dust emission dimmer (Soon et al. 2019; Ueda et al. 2020). However, high spatial resolution data for SY Cha have been taken only in Band 6 presented in this thesis. Thus, I have ignored the dust scattering and estimated the lower limit of the

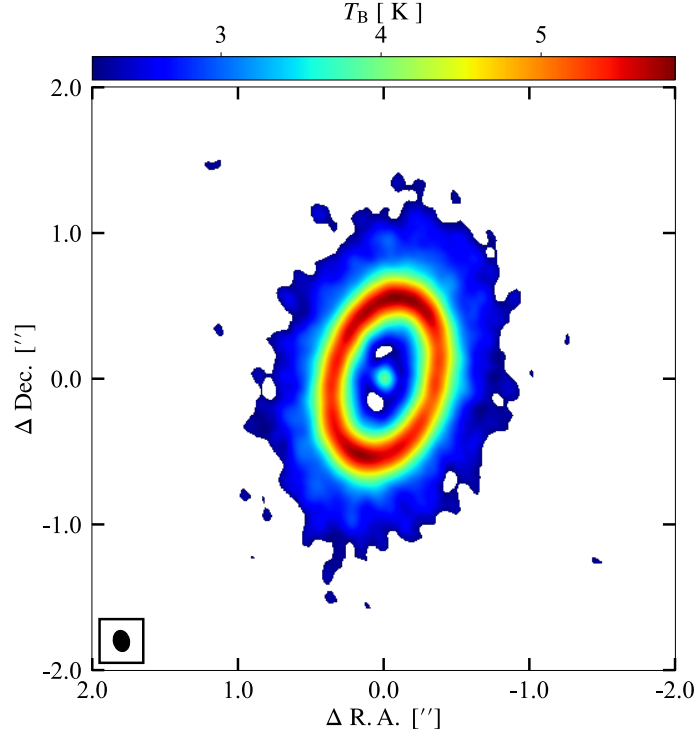


Figure 3.16: Brightness temperature of the dust. The black ellipse at the bottom-left shows the synthesized beam of the dust continuum image. The area where the emission is less than 3σ is indicated in figure 3.1(a) is masked, where $1\sigma = 17.5 \mu\text{Jy/beam}$. The brightness temperature indicates the lower limit of the dust temperature.

optical depth of the dust ring τ_d at 225 GHz.

The lower limit of the total dust mass of the central compact ring is $\approx 0.1 M_\oplus$ ($\approx 3 \times 10^{-7} M_\odot$) (see figure 3.15). This suggests that the inner ring might have a similar mass and orbit to Mercury in our solar system. In addition, there is no remarkable excess emission at $\lambda \lesssim 3\mu\text{m}$ in the SED of SY Cha, as described in chapter 1. This indicates that the disk does not harbor hot ($\gtrsim 1000$ K) dust particles within at least ~ 0.1 au from the central star (see Equation (3.5)). Although the central point source is not spatially resolved even with the EC only image, I consider that the central compact source has a ring-like structure as indicated in the case of DM Tau (Kudo et al. 2018). The upper limit of the size of the central ring is ~ 3.5 au since the beam size of the EC data is ~ 7 au (table 3.3).

The pressure scale height h_d is defined by c_s/Ω_K , where c_s and Ω_K are the sound speed and angular velocity of the Keplerian rotation, respectively. The thickness of gas can be estimated as $2h_d = 26$ au at a radius of 102 au when the temperature distribution is expressed by Equation (3.5). Because the mm-size dust is sometimes concentrated near

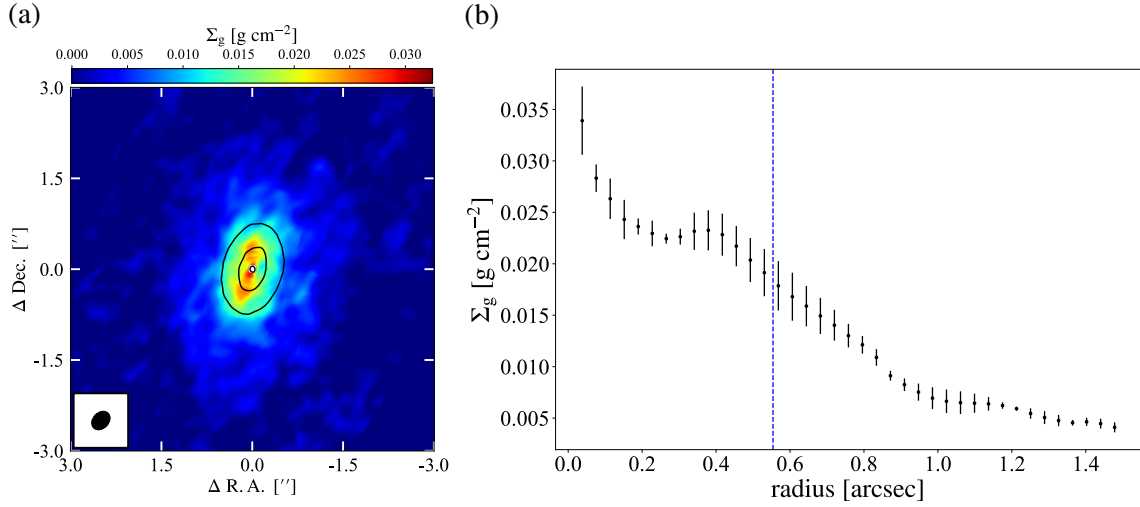


Figure 3.17: (a): Gas column density Σ_g under the assumptions of LTE and the temperature distribution expressed by Equation (3.5). The synthesized beam size is shown at the bottom left. (b) Radial profile of the gas column density along the major axis in (a), which was combined with each side. The error bar is the standard deviation of the mean within the range of ± 10 mas. The blue dashed lines indicate the peak position of dust ring.

the disk mid-plane, this estimate gives the upper limit of the thickness of the dust ring. If dust particles are well mixed with gas, however, the thickness is comparable to the ring radial width of 34 au (table 3.4), suggesting that the outer ring has a torus-like shape. Such geometry is also indicated in Sz 91 system (Tsukagoshi et al. 2019). The derived dust column density is higher at the major axis of the outer ring (figure 3.15), which seems also consistent with the torus-like structure.

3.3.2 Gas Column Density

I estimated the gas column density using the results of the $^{13}\text{CO}(2-1)$ emission, assuming local thermal equilibrium (LTE). I first derived the optical depth of the gas τ_g for each channel map by

$$I_g = B_\nu(T_g)(1 - \exp(-\tau_g)), \quad (3.8)$$

where T_g is the adopted gas temperature, expressed by Equation (3.5). The optical depth τ_g at each position of a channel map is integrated along the velocity axis, and then converted into a column density of ^{13}CO , as described in detail in appendix J. Figure 3.17(a) is the map of Σ_g under the assumption of the abundance ratio of $^{13}\text{CO}/\text{H}_2 = 1/60 \times 10^{-4}$ (Frerking et al. 1982; Wannier et al. 1982). Figure 3.17(b) shows the radial profile of the

gas column density along the major axis. The peak of the gas column density (≈ 0.4 arcsec) may be located inside the dust ring. The total gas mass is estimated to be $2.6 \times 10^{-4} M_{\odot}$. The total integrated flux of $C^{18}O$ corresponds to the total gas mass of $\sim 6.5 \times 10^{-4} M_{\odot}$ assuming the $C^{18}O$ abundance of $C^{18}O/H_2 = 1.79 \times 10^{-7}$ (Wilson 1999), which is consistent with the gas mass estimated from ^{13}CO emission within a factor of 2. The total gas mass is comparable with that of dust mass. However, the abundance of CO in protoplanetary disks may be lower than ISM values by two orders of magnitude (Zhang et al. 2020) and therefore the gas mass may be underestimated by a factor of 10–100.

Chapter 4

Discussion

I detected the distortion of the line-of-site velocity pattern that cannot be explained by the Keplerian rotation of a geometrically thin disk. As shown in figure 3.5 (b), the iso-velocity contour close to the center deviates from the minor axis of the ring by $\sim 25^\circ$. Figure 4.1 shows a part of channel maps of $^{12}\text{CO}(2-1)$ emission obtained by the concatenated (EC+CC) data. Each panel compares the distribution of components blue-shifted and red-shifted by the same amount from the systemic velocity. The distortion of the velocity pattern can be observed in all the panels up to $\Delta V = \pm 4.2$ km/s, and the direction of the velocity gradient appears to change with velocity.

Other transitional disk systems show velocity distortion in the vicinity of the central star (e.g., Casassus et al. 2015; Mayama et al. 2018). There are two possible mechanisms causing similar velocity distortion patterns: radial flow and warped inner disk (e.g., Rosenfeld et al. 2014). Here, I discuss these two possibilities for the SY Cha system.

4.1 Radial Flow

In this subsection, I discuss the possibility of radial flows in the disk. In the vicinity of the central star, the line-of-site velocity is blue-shifted in the east and red-shifted in the west along the minor axis of the outer ring. Because the far-side of the disk is in the east (see chapter 3), this distribution indicates that the velocity vector should be oriented towards the central star. Thus, fast infall may be happening in the vicinity of the central star. As shown in the PV-diagram along the minor axis of the outer disk (figure 3.7(b)), I confirmed the non-zero velocity components within several tens of au. The infall velocity v_{in} and the line-of-sight velocity v_{los} along the minor axis of the outer ring are related by $v_{\text{in}} = v_{\text{los}} / \sin i$, where i is the inclination of the outer ring. For $v_{\text{los}} \sim 2-4$ km/s at ~ 0.1 arcsec from the central star, the infall velocity is inferred to be 2.5–5 km/s at the deprojected distance of ~ 30 au from the central star.

From the infall velocity, I can estimate the mass infall rate $\dot{M} = 2\pi r \Sigma_g v_{\text{in}}$, where Σ_g

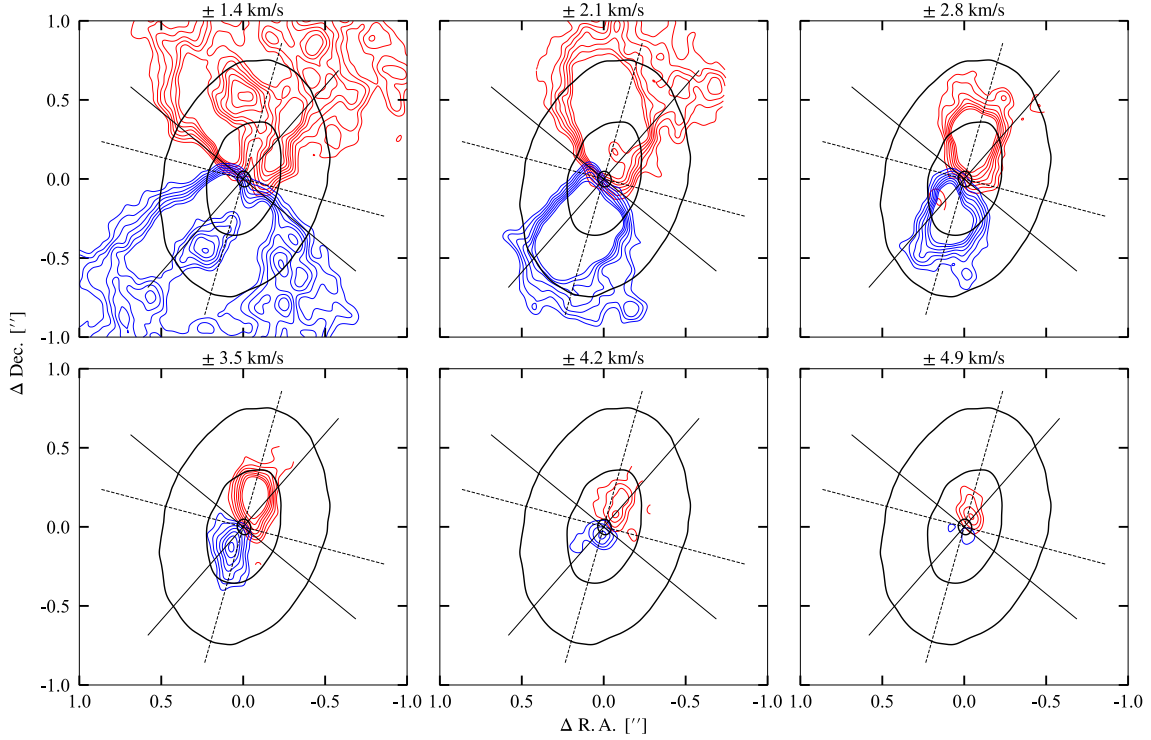


Figure 4.1: Channel map of the $^{12}\text{CO}(2-1)$ emission imaged at a channel width of 0.7 km/s. The velocities based on the systemic velocity ($V_{\text{LSRK}} = 4.1$ km/s) are labeled at the top of each plot. The red and blue contours denote the redshifted and blueshifted emissions, respectively. The contour levels are $3 \sim 9\sigma$, where the 1σ level is 1.37 mJy/beam. The dashed lines represent the major and minor axes of the outer disk ($\text{PA} = -15.3^\circ$). The solid lines are the major and minor axes of the inner disk ($\text{P.A.} = -40^\circ$).

is the gas surface density at radius r . For the estimation of Σ_g , I can employ $^{12}\text{CO}(2-1)$ emission. Because $^{12}\text{CO}(2-1)$ emission can be optically thick, this estimate provides the lower limit of the gas surface density, thus the lower limit of the mass infall rate. Figure 4.2 shows the radial distribution of gas surface density derived from $^{12}\text{CO}(2-1)$ assuming the temperature expressed by equation (3.5) and the gas surface density at ~ 0.1 arcsec from the central star is ~ 0.003 g/cm $^{-2}$ for the standard CO/H $_2$ ratio of 10^{-4} . This is significantly lower than the gas surface density using ^{13}CO data (figure 3.17), and the actual gas surface density can even be higher if CO is depleted (see chapter 3.3.2). However, this gas surface density results in an estimate of the mass infall rate of $\sim 10^{-8} M_\odot/\text{yr}$ at $r \sim 30$ au from the central star, which is considerably higher than the stellar mass accretion rate of $\sim 3.89 \times 10^{-10} M_\odot/\text{yr}$ derived from VLT/X-shooter spectra (Manara et al. 2017).

The evolution of protoplanetary disks is significantly affected by magnetic flux dis-

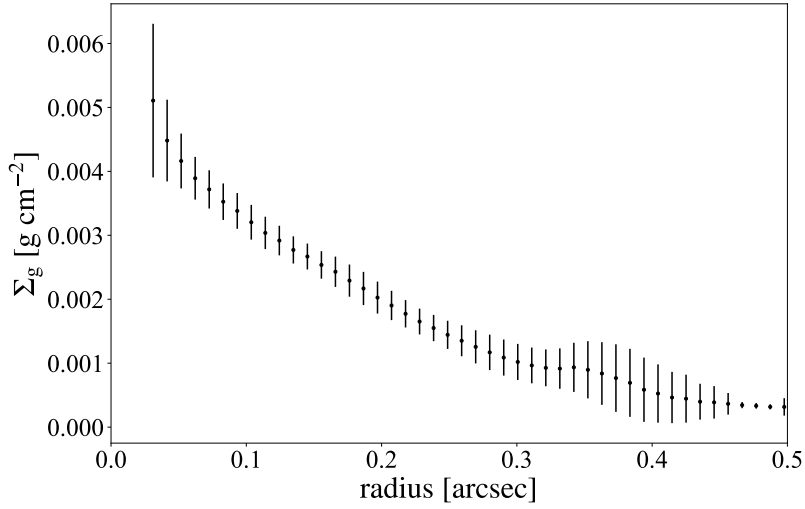


Figure 4.2: Radial profile of the gas column density calculated from ^{12}CO along the minor axis, which was combined with each side. The error bar is the standard deviation of the mean within ± 10 mas.

tribution (Tsukamoto et al. 2015a, Tsukamoto et al. 2015b, Bai & Stone 2017), and the wind-driven accretion by magnetohydrodynamic (MHD) effects play an important role in the mass loss process and angular momentum transport (Bai & Stone 2013; Suzuki et al. 2016). One possible scenario that explains the velocity distortion caused by radial flow while maintaining a low stellar mass accretion rate is the combination of fast accretion only in the upper layer of the disk and disk wind. The mass accretion rate is low in the close vicinity of the star, probably because the accreting materials in the upper layer of the disk are loaded on magnetic field lines, and are disposed as disk wind (e.g., Sheikhezami et al. 2012). However, the wind mass loss rate is probably a few times the stellar mass accretion rate at most (Hasegawa et al. 2021), and therefore, it may be difficult to load almost all the accreting material from the outer disk onto the disk wind.

4.2 Warp

If the system has a warp structure, I expected the existence of a misaligned inner dust disk (Casassus et al. 2018). In this subsection, I assumed that the disk system has a misalignment between the inner and outer rings. The PA of the disk major axis should be along the direction with the highest line-of-sight velocity gradient; therefore, I assumed that the major axis of the inner ring is along the PA of -40° (shown in figure 3.5).

Figure 4.3(a) shows the residual intensity map shown in figure 3.13(a) projected onto

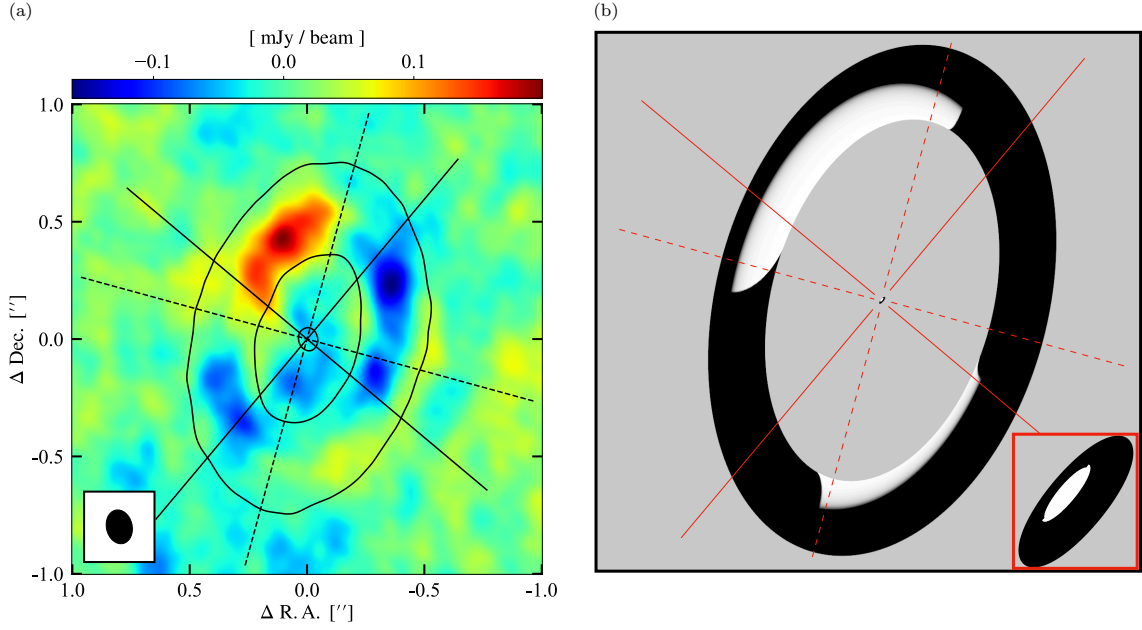


Figure 4.3: (a): Residual map projected figure [3.13\(a\)](#). The synthesized beam size ($0.146'' \times 0.110''$) is shown at the bottom-left. The black contour indicates the 20σ level of the dust continuum, where $1\sigma = 17.5 \mu\text{Jy}/\text{beam}$. The dashed lines show the major and minor axes of the outer ring. The solid lines show the major and minor axes of the inner disk. (b): Schematic diagram of the torus model that has an inner ring (PA= -40° , inc.= 75°) and the outer ring (PA= -15.3° , inc.= 51.7°), setting the radius ratio between the outer and the inner torus to 102:3, and the scale height of the two rings relative to their radius to be 0.2. Like with (a), the red lines show the major and minor axes of the inner ring shown at the bottom-right corner, and the red dashed lines show that of the outer ring.

the plane of sky using the outer ring inclination (51.7°) and position angle (-15.3°). As shown in the figure, the residual pattern is brightest in the northeast direction, which is similar to the direction along the minor axis of the inner disk, as suggested by the velocity gradient. A misaligned inner disk can cast a shadow onto the outer disk, causing azimuthally asymmetric illumination ([Marino et al. 2015](#)). This asymmetric illumination may cause temperature variations on the ring, thereby causing asymmetry of the dust continuum emission. Our observations show that the degree of azimuthal asymmetry along the outer ring is only $\sim 15\%$. This suggests that the difference in temperature in the bright and dark regions is only a few Kelvin, while the average temperature of the outer ring is ~ 30 K. This temperature difference may be caused by the asymmetric illumination pattern caused by the inner disk.

Here, I investigate the shadow cast by the inner disk using a simplified model with

the 3D graphics software Blender (<https://blender.jp>). I considered two optically thick misaligned rings sharing the same center where a point light source is placed (figure 4.3(b)). The outer ring has the same position angle and inclination as observed (PA = -15.3° , inc. = 51.7°), while the inner ring has a position angle of -40° , which is indicated by the observed velocity distortion. Thereafter, I varied the inclination of the inner ring to investigate the changes in the illumination pattern on the outer disk. I set the radius ratio between the outer and inner torus to 102:3 and the scale height of the two rings relative to their radius to be 0.2. I found an illumination pattern similar to figure 4.3(a) when the inner disk has an inclination of $70\text{--}90^\circ$ (figure 4.3(b)). The northeast part of the outer ring is illuminated, and the temperature of this part may be higher than that of the other parts. Moreover, the inner disk with an inclination of $70\text{--}90^\circ$ is consistent with the observed velocity distortion of a few km/s, because the Keplerian velocity at $r \sim 0.1$ arcsec ≈ 20 au along the major axis of the inner disk is 6 km/s.

Therefore, the misaligned inner disk is a plausible interpretation of the velocity distribution and dust asymmetry. To obtain a realistic temperature distribution, rather than an illumination pattern, I need full radiative transfer modeling, which will be presented in a future work.

Detailed study of the warped inner disk is left to a future work. As one of the approaches, I propose to conduct an observation of rovibrational CO line emission at $4.7\text{ }\mu\text{m}$ toward SY Cha. This line is formed in the heated surfaces of the disk at radius of 0.1–10 au (Brown et al. 2013), the compact inner gas disk thus is expected to be traced. Pontoppidan et al. (2008) observed CO $4.7\text{ }\mu\text{m}$ line in protoplanetary disk around SR 21, HD 135344B and TW Hya using the CRIRES high-resolution infrared spectrometer on the Very Large Telescope (VLT) and estimated PA and inclination of the inner disks to within a few degrees.

Software: astropy, CASA, Numpy, Matplotlib, emcee, keplerian_mask, bettermoments, Blender

Chapter 5

Conclusions

I reported ALMA observations of the transitional disk around SY Cha. The dust continuum emission and the $J=2-1$ line emission of CO isotopologues at Band 6 were observed. My conclusions are summarized as follows;

1. The 225 GHz dust continuum emission shows a clear ring structure with the radius of ~ 100 au and the central point sources. The total dust mass is estimated to be $1.2 \times 10^{-4} M_{\odot}$. I suggested that the central point source is actually a ring because the SED does not show a significant IR excess. From visibility-domain analyses, I found extended emission outside the outer ring and weak asymmetry in the outer ring. The asymmetry shows that the ring is bright in the north-east direction.
2. I detected all ^{12}CO , ^{13}CO and C^{18}O emission. The moment 0 maps of the ^{13}CO and C^{18}O emissions show a ring-like structure, while ^{12}CO emission is detected inside the dust ring, indicating that there is some gas remaining inside the dust ring. Assuming that ^{12}CO is a tracer of disk temperature, I estimated the total gas mass as $2.6 \times 10^{-4} M_{\odot}$ and the peak column density of the disk gas as $\sim 0.025 \text{ g/cm}^2$ if CO is not depleted. Although the result corresponds to a gas-dust mass ratio of approximately 1, the estimated gas value may be increased by a factor of 10–100 by CO depletion.
3. The moment 1 map of the CO line emission shows that the velocity pattern agree with the Keplerian rotation around $0.78 M_{\odot}$; however, the velocity pattern in the vicinity of the central star is distorted. The origin of the velocity distortion is yet inconclusive. If the velocity distortion is caused by radial flow, the mass inflow rate at ~ 30 au is well above the stellar mass accretion rate, indicating that a significant amount of mass is being ejected as disk wind. If the velocity distortion is caused by a warped inner disk, I expected that the inner disk is close to edge-on (inclination of $70-90^\circ$). The weak asymmetry of the outer disk is consistent with the asymmetric illumination of the central star caused by the warped inner disk.

Appendix A

ALMA Pipeline Calibration

The ALMA science pipeline provides an automated calibration and imaging procedure which produces standard science quality data products for both radio expert and non-radio expert astronomers (Geers et al. 2019). The pipeline tasks are designed to be modular, each can be run via the CASA task interface or as part of an automated Python script. The pipeline tasks become available by starting up CASA using the command:

```
casa —pipeline
```

In general, to restore pipeline calibrated data, we have to run the `scriptForPI.py`, which is basically only compatible with CASA versions similar to the one used for its creation. The `scriptForPI.py` could run using the command:

```
execfile('scriptForPI.py')
```

Tables A.1 and A.2 show description of the pipeline tasks (ALMA Science Pipeline User's Guide for CASA 5.4 2018; ALMA Science Operations: Cycle 6 Pipeline Reference Manual 2018).

Table A.1: pipeline task

task name	description
<code>hifa_importdata</code>	This task loads the specified visibility data into the pipeline context unpacking and/or converting it as necessary.
<code>hifa_flagdata</code>	The data performs basic flagging operations on a list of MeasurementSets.
<code>hifa_fluxcalflag</code>	Locate and flag line regions in solar system flux calibrators. Fills the model column with the model visibilities.
<code>hif_rawflagchans</code>	Flags deviant baseline/channels in the raw data.

Table A.2: pipeline task

task name	description
<code>hif_refant</code>	Selects a list of reference antennas and outputs them in priority order. The priority order is determined by a weighted combination of scores derived by the antenna selection heuristics.
<code>h_tsyscal</code>	Derive the Tsys calibration for list of ALMA MeasurementSets.
<code>hifa_tsysflag</code>	Flag deviant system temperatures for ALMA interferometry measurements.
<code>hifa_antpos</code>	Derive an antenna position calibration table.
<code>hifa_wvrgcalflag</code>	This task will first identify for each vis whether it includes at least 3 antennas with Water Vapor Radiometer (WVR) data, and that the fraction of WVR antennas / all antennas exceeds the minimum threshold.
<code>hif_lowgainflag</code>	Flags data for antennas with unusually low or high gains.
<code>hif_setmodels</code>	Derive flux densities for point source transfer calibrators using flux models for reference calibrators.
<code>hifa_bandpassflag</code>	Compute bandpass calibration with flagging.
<code>hifa_spwphaseup</code>	Compute phase calibration spw map and per spw phase offsets.
<code>hifa_gfluxscaleflag</code>	Derive the flux density scale with flagging.
<code>hifa_gfluxscale</code>	Derive flux densities for point source transfer calibrators using flux models for reference calibrators.
<code>hifa_timegaincal</code>	Determine temporal gains from calibrator observations.
<code>hif_applycal</code>	Apply precomputed calibrations to the data.
<code>hif_makeimlist</code>	Create a list of images to be cleaned.
<code>hif_makeimages</code>	Compute a cleaned image for a particular target source/intent and spectral window.
<code>hifa_imageprecheck</code>	The representative source and spw containing the representative frequency selected by the PI in the ALMA Observing Tool (OT) are used to calculate the synthesized beam and to make sensitivity estimates for the aggregate bandwidth and representative bandwidth for several values of the robust parameter.
<code>hif_checkproductsizes</code>	Check interferometry imaging product size and try to mitigate to maximum allowed values.

Appendix B

Visibility weighting

With reference to [Thompson et al. \(2017\)](#), I explain the visibility weighting.

In radio interferometry study, the Fast Fourier transform (FFT) is often used to make image from measured visibility. The speed of the fast algorithm for the FFT is a major advantage in computing large images. At this time, a gridding is used to transform visibility values into uniformly sampled grid points (see figure [B.1](#)). the visibility samples in each grid cell is given a weight in the imaging step. This weighting can be used to account for differences in the density of sampling in different parts of the (u, v) plane, or to improve sensitivity to extended objects. Here I briefly review some weighting schemes.

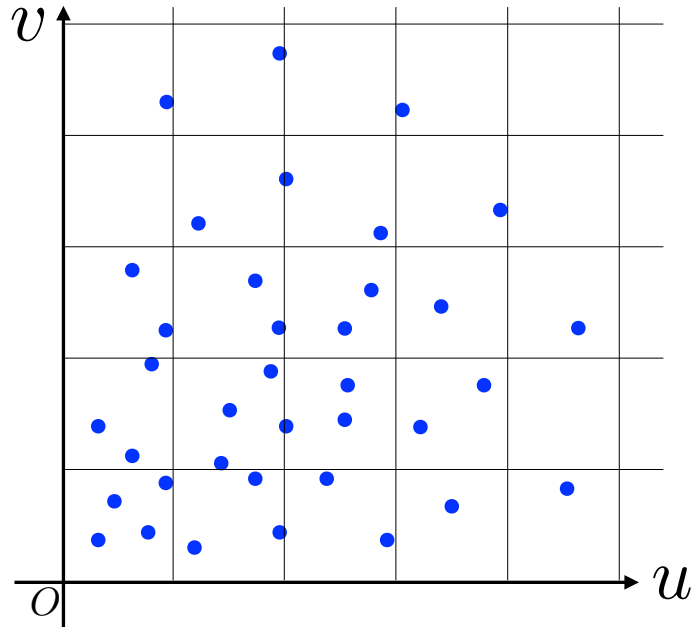


Figure B.1: Visibility samples (blue points) and grid lines (solid lines) on the (u, v) plane.

B.1 Density weighting

- **Natural weighting**

This gives constant weights to all visibilities (or, more strictly, inversely proportional to the noise variance of a visibility). This weighting gives optimum point-source sensitivity in an image. However the synthesised beam-shape and sidelobe levels are usually poor.

- **Uniform weighting**

This gives a weight inversely proportional to the sampling density. This form of weighting minimises the sidelobe level. However the noise level can be a factor of 2 worse than natural weighting.

- **Briggs weighting**

Uniform weighting minimising sidelobes, whereas natural weighting minimises the noise level. Briggs weighting provides a compromise between the two, doing so in an optimal sense. The weighting of cell (i, k) in the (u, v) plane whose visibility has an rms error of σ_{ik} is specified as

$$w_{ik} = \frac{1}{S^2 + \sigma_{ik}^2}, \quad (\text{B.1})$$

$$S^2 = \frac{(5 \times 10^{-R})^2}{\bar{w}}, \quad (\text{B.2})$$

$$\bar{w} = \frac{1}{n_c} \sum \frac{1}{\sigma_{ik}^2}, \quad (\text{B.3})$$

where R is the robustness factor (-2 to 2), and $\bar{w}$ is the average variance weighting factor over the n_c cells in the image. $R = 2$ makes S very small with respect to w so that the weighting approaches natural weighting, whereas $R = -2$ makes S large with respect to w so that the weighting approaches the uniform weighting.

B.2 uv-taper

The uv-taper applies a multiplicative Gaussian to the spatial-frequency grid, to weight down high spatial-frequency measurements relative to the rest. This suppresses artifacts arising from poorly sampled regions near and beyond the maximum spatial frequency and significantly increases the detectability of an extended source. However, it also degrades the resolution. Gaussian weighting can be combined with any of the above weighting schemes to achieve some form of balance between sidelobes and sensitivity.

Appendix C

CLEAN

With reference to [Cornwell \(2008\)](#) and [Thompson et al. \(2017\)](#), I explain the CLEAN algorithm.

Radio synthesis arrays image the radio sky not through a single large physical aperture but by synthesising a virtual aperture of equivalent size and angular resolution. This is done by invoking the van Cittert-Zernike theorem relating the visibility and the intensity:

$$V(u, v) = \mathcal{F}[I(x, y)]. \quad (\text{C.1})$$

For a real array, the completely sampled visibility function $V(u, v)$ is not available and we have only incomplete samples of the visibility at discrete locations in the (u, v) plane. Ignoring for the moment the effects of noise, we can represent this by replacing $V(u, v)$ by the sampled visibility function $S(u, v)V(u, v)$, where the sampling function $S(u, v)$ is:

$$S(u, v) = \sum_k w_k \delta(u - u_k) \delta(v - v_k), \quad (\text{C.2})$$

where w_k is weight for each visibility data.

Inserting this into the Fourier inverse, we then obtain the dirty image:

$$I^D(x, y) = \mathcal{F}^{-1}[S(u, v)V(u, v)]. \quad (\text{C.3})$$

Applying the convolution theorem from Fourier transform theory, we find that the dirty image is the convolution of the true image I with a synthesized beam B (figure [C.1](#)):

$$I^D(x, y) = B * I(x, y). \quad (\text{C.4})$$

where the synthesized Beam or Point Spread Function $B = \mathcal{F}^{-1}[S]$ is given by:

$$B(x, y) = \sum_k \cos(2\pi(u_k x + v_k y)) w_k. \quad (\text{C.5})$$

Thus the deconvolution problem is to solve for I from knowledge of the dirty image I^D , and the point spread function B .

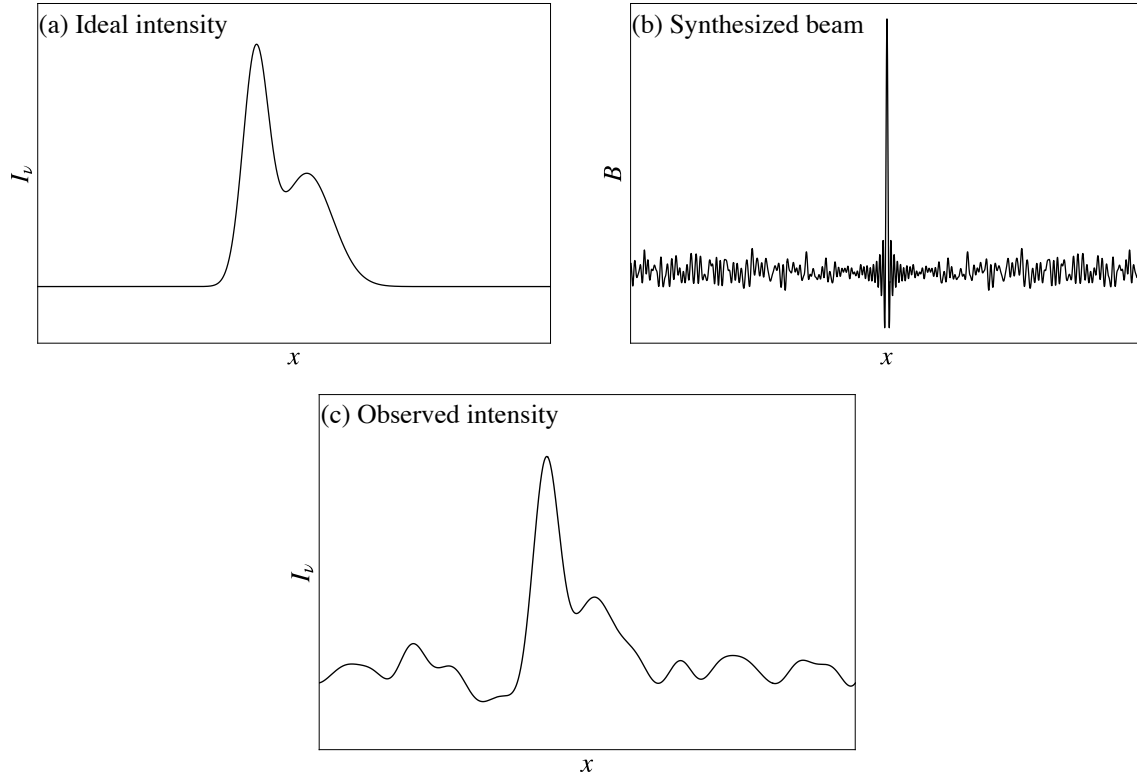


Figure C.1: The observed intensity is interpreted as the convolution of the ideal intensity with a synthesized beam.

C.1 CLEAN algorithm

Högbom CLEAN is a basic numerical deconvolving process usually applied in the image domain (Högbom 1974). The CLEAN algorithm represents the image as a number of point sources in an otherwise empty field of view. A simple iterative procedure is used to find the locations and strengths of these point sources. The CLEAN algorithm looks for the brightest pixel (called a CLEAN component) in a specified region in the image (figure C.2). Having found this peak pixel, it subtracts a fraction (called the loop gain, and generally about 0.1 or less) of the synthesized beam from the residual (dirty) image at the location of that brightest pixel. This subtracted image is called the residual image. The search and subtraction loop is repeated until the sidelobes in the image are reduced to below the noise level. Performance of the deconvolution can be improved by restricting the search to a region wherein the image brightness is expected to be non-zero.

In the end, we convolve the delta functions in the cleaned model with a CLEAN beam response B_G , that is, replace each delta function with a CLEAN beam function of corresponding amplitude (figure C.3). The clean beam is often chosen to be a Gaussian with a half-amplitude width equal to that of the original synthesized beam. Moreover,

adding the residuals into the convolved image, which is then the output of the process. When the residuals are added, the Fourier transform of the image is equal to the measured visibilities.

The scheme for the Högbom CLEAN algorithm is presented in Algorithm 1. CLEAN is a greedy algorithm: it consists of a sequence of iterations, and within each iteration, the choice made depends only on information available at the iteration. There is no guarantee that the result of the CLEAN algorithm is globally optimal in any particular sense, although there is a conjecture that the image L1 norm is minimized (Marsh & Richardson 1987). The interpretation of Högbom CLEAN in Compressive sensing has been developed as a matching pursuit algorithm calculating residual vectors in image space (Li et al. 2011).

Algorithm 1 Högbom CLEAN

Initialize:

Model: $I^M = 0$

Residual Image: $I^R = I^D$

Repeat:

- (1) Find strength and location of peak residual
- (2) Add this component to current model, scaled by loop gain
- (3) Update residual image using precomputed terms

Until:

Either $\max(I^R) < \text{threshold}$

Or Maximum number of components identified

Finalize:

Convolve current model by clean beam: $B_G * I^M$

Add residuals to get restored image: $B_G * I^M + I^R$

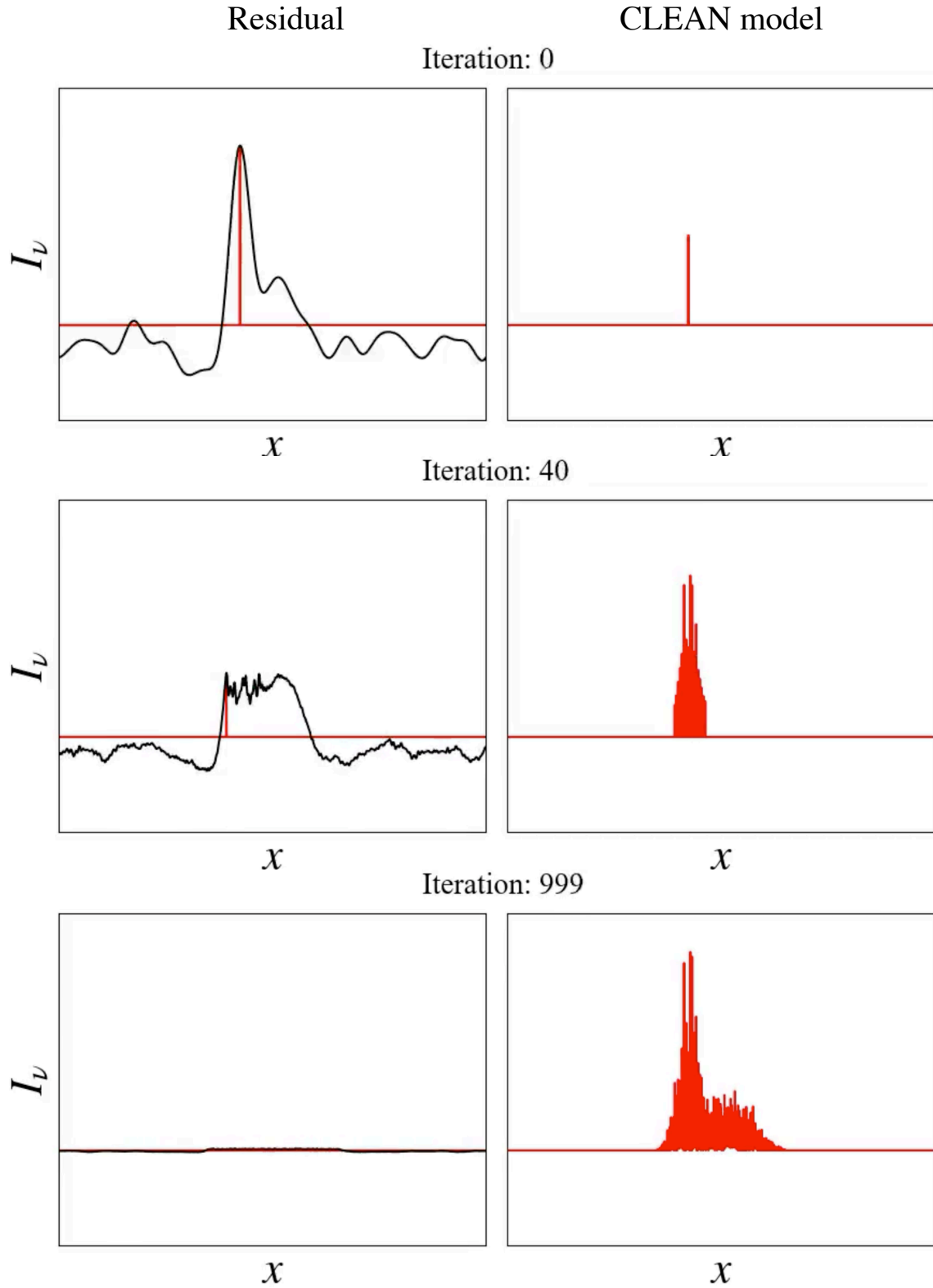


Figure C.2: Residual and CLEAN model in each iteration. Having found this peak point, it subtracts a fraction of the synthesized beam from the residual at the location of that brightest point.

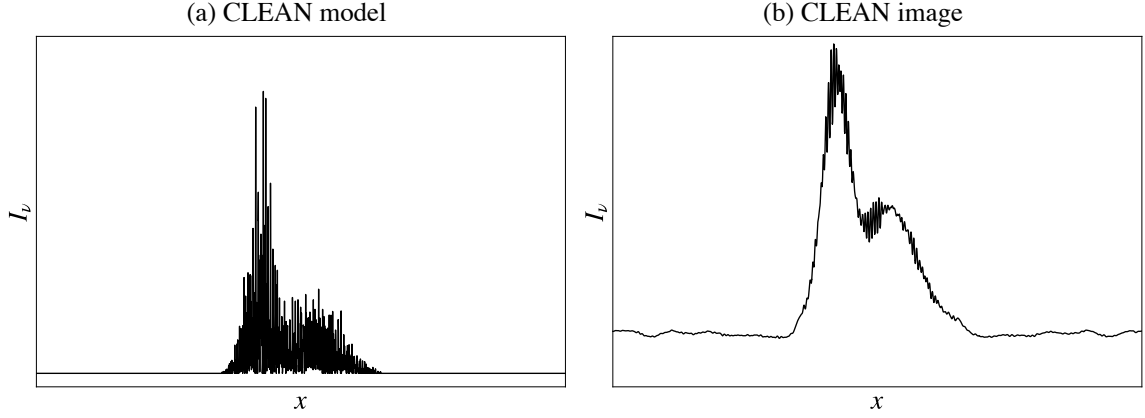


Figure C.3: The CLEAN image (b) is outputed as the image which convolved the model (a) with CLEAN beam and added to the final residuals.

C.2 Multi-Scale CLEAN

The model is based on the assumption that the true sky brightness is a summation of appropriately scaled and centered extended components. Denoting the component width by a single parameter α_q , the model is expressed by:

$$I^M = \sum_q I_q m(x - x_q, y - y_q, \alpha_q). \quad (\text{C.6})$$

Following the greedy strategy used in the CLEAN algorithm, we search for the n th component by looking for a peak in:

$$I^R(n) = I^D - B * I^M(n-1) \quad (\text{C.7})$$

where the search is over I_q, x_q, y_q, α_q . In deciding which scale to select, we must apply a bias towards smaller scales. We evaluate the maximum residual for a set of scale sizes, and choose that scale size with the maximum adjusted residual.

$$S(\alpha) = 1 - 0.6 \frac{\alpha}{\alpha_{\max}} \quad (\text{C.8})$$

In any iteration, the component selected is thus located at the peak with the appropriate scale size. The magnitude of the component is given by the loop gain times the peak. The algorithm can be made efficient by careful precomputation of all terms that are needed for the update:

$$B * m(\alpha_q), B * m(\alpha_p) * m(\alpha_q) \quad (\text{C.9})$$

[Cornwell \(2008\)](#) have chosen a tapered, truncated parabola as the component shape:

$$m(r, \alpha) = \Psi(r) \left(1 - \left(\frac{r}{\alpha} \right)^2 \right) \quad (\text{C.10})$$

where Ψ is a prolate spheroidal wave function. The difference between this function and a suitably scaled Gaussian is quite minor. For zero α , this corresponds to a Dirac delta function.

The scheme for the MS-CLEAN algorithm is presented in Algorithm 2 (Cornwell 2008).

Algorithm 2 MS-CLEAN

Initialize:

Model: $I^M = 0$

Residual Image: $I^R = I^D$

For each scale α_q

– calculate scale-convolved residual $I_\alpha^R = m(\alpha) * I^R$

– calculate scale bias $S(\alpha) = 1 - 0.6 * \alpha / \alpha_{\max}$

For each pair of scales α_p, α_q , calculate cross term: $B * m(\alpha_p) * m(\alpha_q)$

Repeat:

- (1) For each scale, find strength and location of peak residual
- (2) Choose scale with maximum residual, after multiplying by scale-dependent bias terms
- (3) Add this component to current model, scaled by loop gain
- (4) Update all residual images using precomputed terms

Until:

Either $\max(I_\alpha^R) < \text{threshold}$

Or Maximum number of components identified

Finalize:

Convolve current model by clean beam: $B_G * I^M$

Add residuals to get restored image: $B_G * I^M + I^R$

Appendix D

Self-Calibration

D.1 Principle of self-calibration

Because the interpolated calibrator gains do not determine the antenna gains perfectly at each time stamp, the quality of the resultant image is limited. The technique of self-calibration is widely used to make additional corrections to the antenna gains as a function of time. The self-calibration procedure is often performed iteratively, each time with a better model, until the sequence converges and no more improvement in the image quality can be made.

With reference to [Thompson et al. \(2017\)](#), I explain the self-calibration. The procedure in self-calibration is to use a least-mean-squares method to minimize the square of the modulus of the difference between the observed visibilities, V_{ij}^{obs} , and the corresponding values for the derived model, V_{ij}^{mod} . The expression that is minimized is

$$\sum_{\text{time}} \sum_{i < j} w_{ij} |V_{ij}^{\text{obs}} - g_i g_j^* V_{ij}^{\text{mod}}|^2, \quad (\text{D.1})$$

where the weighting coefficient w_{mn} is usually chosen to be inversely proportional to the variance of V_{ij}^{obs} , and the quantities shown are all functions of time within the observing period. Equation (D.1) can be written

$$\sum_{\text{time}} \sum_{i < j} w_{ij} |V_{ij}^{\text{mod}}|^2 |X_{ij} - g_i g_j^*|^2, \quad (\text{D.2})$$

where

$$X_{ij} = \frac{V_{ij}^{\text{obs}}}{V_{ij}^{\text{mod}}}. \quad (\text{D.3})$$

If the model is accurate, the ratio X_{ij} of the uncalibrated observed visibility to the visibility predicted by the model is independent of u and v but proportional to the antenna gains. Thus, the values of V_{ij} simulate the response to a calibrator and enable the gains to be

determined. However, since the initial model is only approximate, the desired result must be approached by iteration.

The self-calibration procedure is:

1. Make an initial model of the source using whatever constraints I have on the source structure.
2. Compute the X_{ij} factors for each visibility integration period within the observation.
3. Determine the antenna complex gain factors for each integration period.
4. Use the gains to calibrate the observed visibility values and make an image.
5. Use CLEAN and select components to provide positivity and confinement of the image.
6. Test for convergence and return to step 2 as necessary.

Self-calibration, like basic calibration, requires that the signal-to-noise ratio on each baseline be of the order of at least 3–5 or so. For weak sources, this may require a long solution interval, within which the gains are assumed to be constant. If, in reality, the gains are changing on a time-scale significantly shorter than your solution interval, and these changes are degrading your image quality, then you will be unable to improve the image quality.

D.2 The self-calibration in my analysis

The self-calibration was performed by using the `gaincal` and `applycal` tasks in the CASA tools. Table D.1 shows the options set in each iteration. The description of options is available at the CASA homepage (<https://casa.nrao.edu/casadocs/casa-6.1.0/global-task-list>). The option `gaintype` was set to ‘T’ in every iteration.

Table D.1: Self-calibration options

iteration	calmode	solint	combine	refant	applymode
CC 1	‘p’	‘inf’	‘spw’	‘DV05, DV21, DV17’	calflag
CC 2	‘p’	180s	‘spw’	‘DV05, DV21, DV17’	calonly
CC 3	‘p’	180s	‘spw’	‘DV05, DV21, DV17’	calflag
CC 4	‘p’	90s	‘spw’	‘DV05, DV21, DV17’	calflag
CC 5	‘ap’	‘inf’	‘obs, scan’	‘DV05, DV21, DV17’	calflag
concat 1	‘p’	‘inf’	‘obs, scan’	‘DA41’	calflag

Appendix E

Dust continuum maps

Figure E.1 (a) and (b) show the dust continuum image in the EC data and the CC data, respectively. I summarize properties of each dust continuum image in table 3.3. The continuum imaging were performed by using the `tclean` task in the CASA tools by setting the options shown in table E.1.

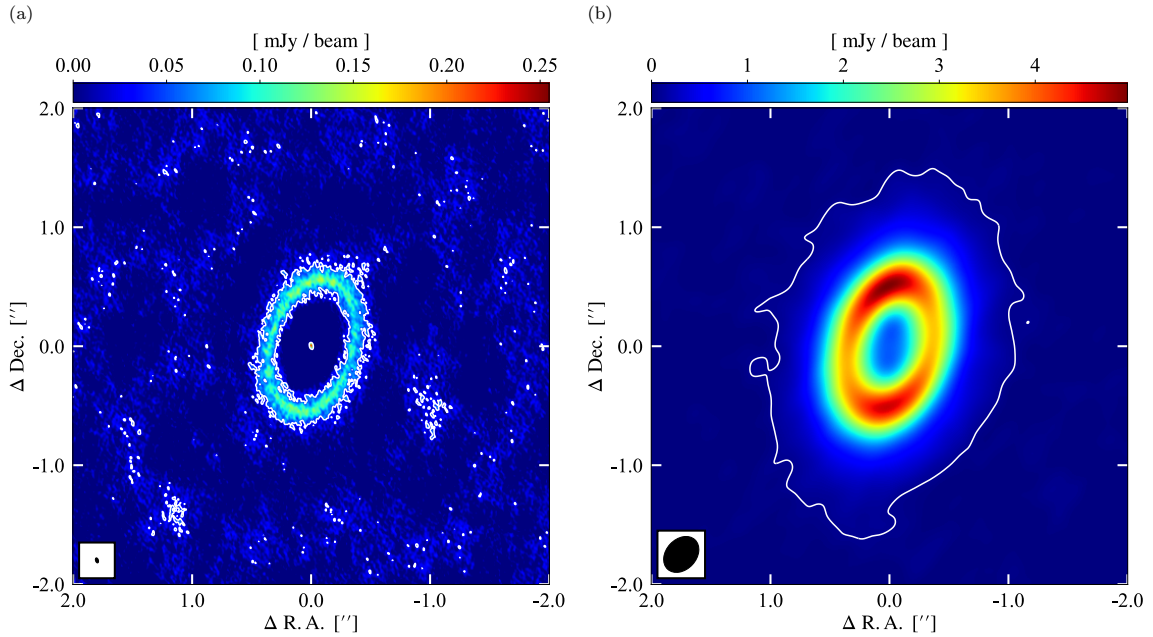


Figure E.1: Dust continuum emission in (a) the EC data and (b) CC data. The black ellipse at the bottom left of each panel represents the beam size. The white contour denotes the 3σ , where the 1σ level is the rms noise (EC data: $13.6 \mu\text{Jy}/\text{beam}$, CC data: $26.7 \mu\text{Jy}/\text{beam}$).

Table E.1: tclean options for continuum imaging

option name	description	value or string
field	Select fields to image.	‘SY_Cha’
datacolumn	Data column to image	‘corrected’
cell	Size of the image pixel	[‘0.005arcsec’]
imsize	Number of pixels	[4096, 4096]
specmode	Spectral definition mode	‘mfs’ (continuum imaging)
deconvolver	Name of minor cycle algorithm	‘multiscale’
scales	List of scale sizes (in pixels) for multi-scale algorithm	[0, beam_pix, 2*beam_pix]
smallscalbias	A numerical control to bias the solution towards smaller scales.	0.4
gain	Fraction of the source flux to subtract out of the residual image for the CLEAN algorithm and its variants.	0.1
gridder	Gridding options	‘standard’
weighting	Weighting scheme	‘briggs’
robust	Robustness parameter for Briggs weighting	2.0
uvtaper	taper on outer baselines in (u, v) plane	‘1500klambda’ (concatenated data)
interactive	Modify masks and parameters at run-time	True
niter	Maximum number of iterations	50000
nterms	Number of Taylor coefficients in the spectral model	2

Appendix F

Method of ellipse fitting

Figure F.1 shows the process of the ellipse fitting in chapter 3.1.1.

The local maxima point (black points) of the radial profile (along the write line) of the surface brightness for every 15° in PA was sampled, as shown in figure F.1(1)–(2). The ellipse with five parameters (2D center position, position angle, length of major and minor axes) was estimated by least-square fitting a set of the samples (figure F.1(3)–(4)).

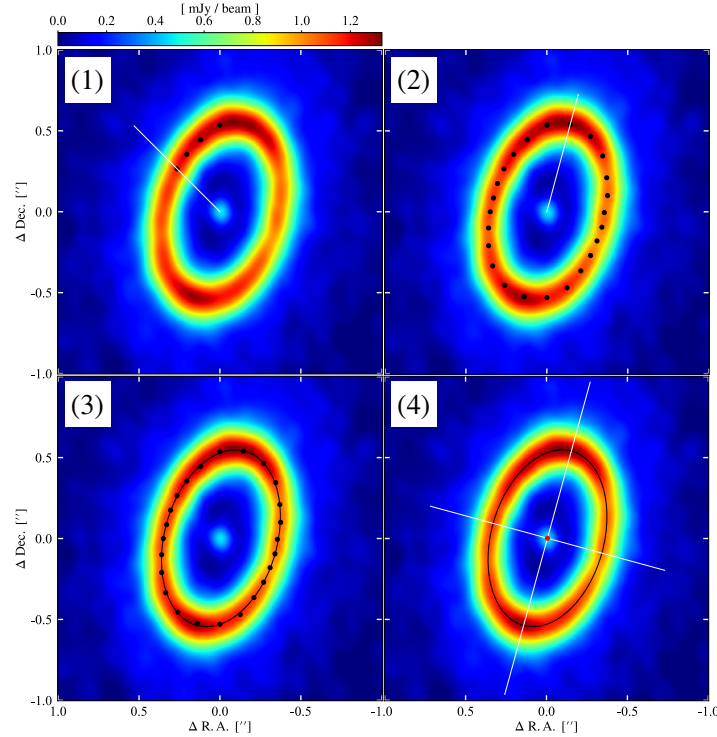


Figure F.1: The process of the ellipse fitting is described in the text. The red point in (4) indicates the center of the best-fit ellipse. The white solid line in (4) denotes the major and minor axes of the ellipse.

Appendix G

Channel Maps

Figures [G.1](#)–[G.4](#) show the channel maps of the CO line emission at $V_{\text{LSRK}} = -4.3$ to $+12.5$ km/s. See table [2.3](#) for information of these channel maps.

The CO isotopologue lines imaging were performed by using the `tclean` task in the CASA tools. Most options were set as with the continuum imaging, I added or changed some options as shown in table [G.1](#).

Table G.1: `tclean` options for CO line imaging

option name	description	value or string
<code>specmode</code>	Spectral definition mode	‘cube’
<code>outframe</code>	Spectral reference frame in which to interpret <code>start</code> and <code>width</code>	‘LSRK’
<code>start</code>	First channel of output cube images specified	‘−4.3 km/s’
<code>width</code>	Channel width of output cube images specified	‘0.7 km/s’
<code>nchan</code>	Number of channels in the output image	25
<code>restfreq</code>	A rest frequency in a string.	‘230.538GHz’ ($^{12}\text{CO}(2-1)$) ‘220.399GHz’ ($^{13}\text{CO}(2-1)$) ‘219.560GHz’ ($\text{C}^{18}\text{O}(2-1)$)

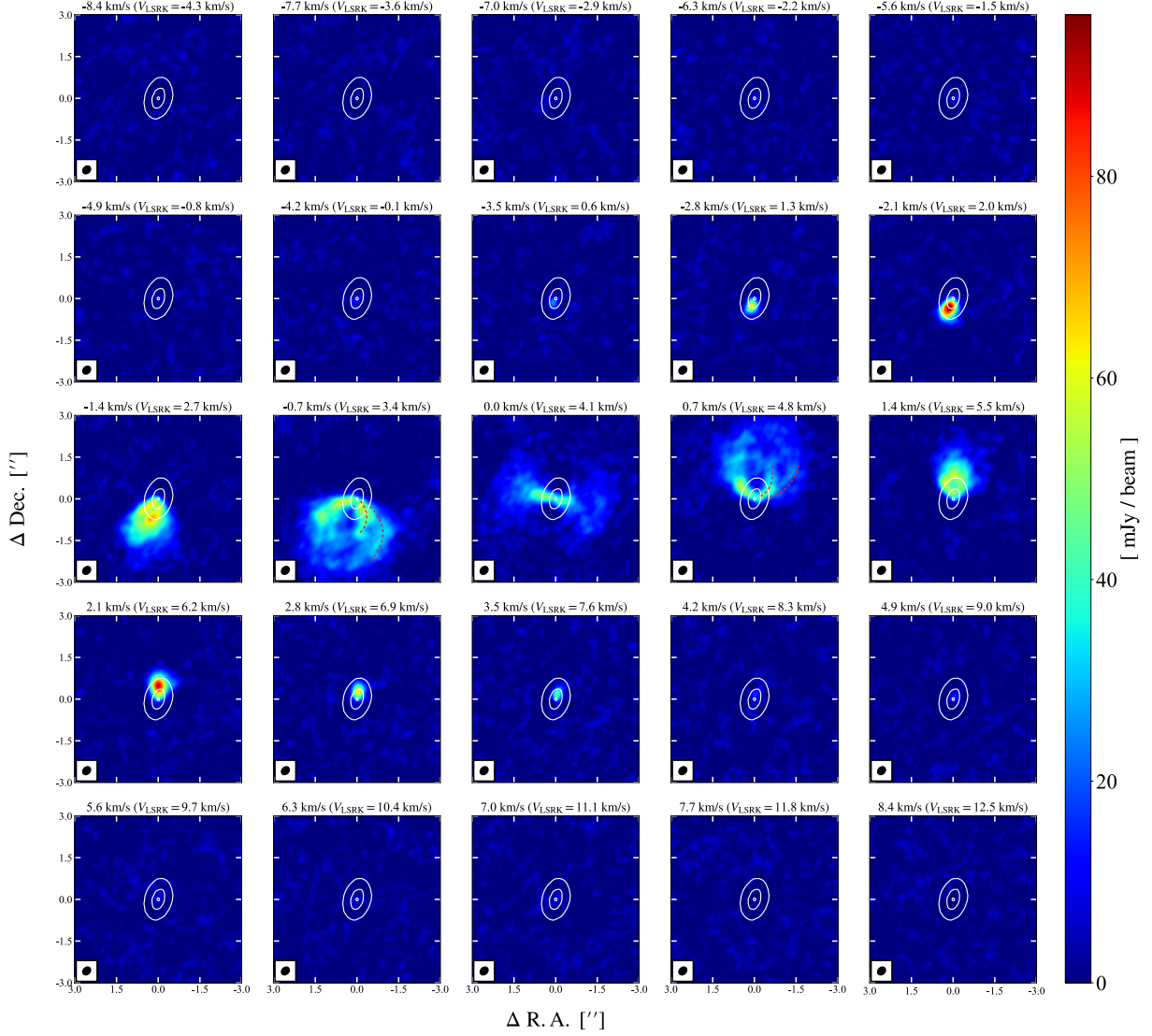


Figure G.1: $^{12}\text{CO}(2-1)$ Channel Map in the CC data. The black ellipse at the bottom left of each panel represents the beam size. The contours in these maps indicate the 20σ level of the dust continuum, where $1\sigma = 17.5 \mu\text{Jy}/\text{beam}$. The twin-line patterns are traced by the red dashed lines on panels of $\Delta V = \pm 0.7$ km/s.

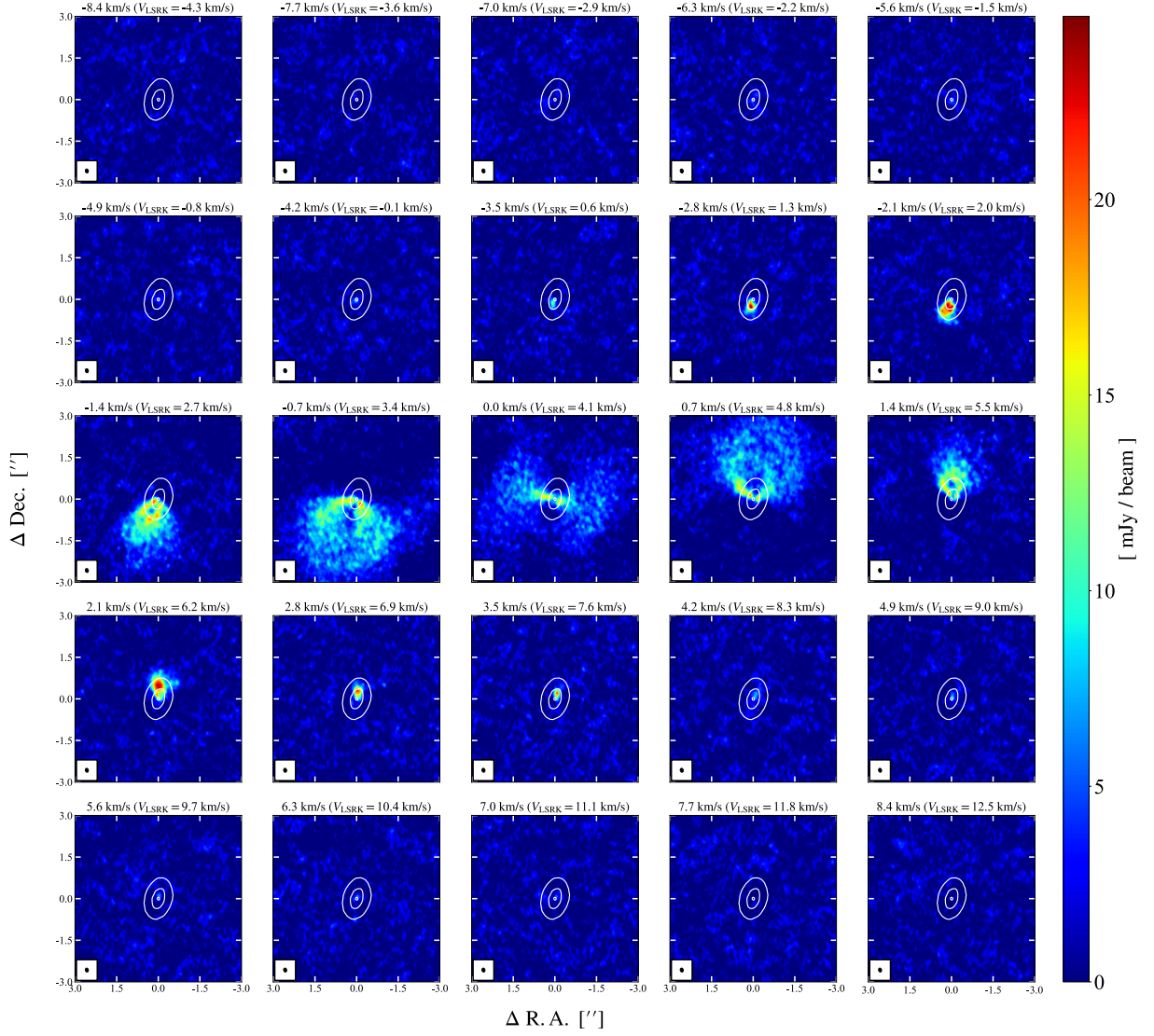


Figure G.2: $^{12}\text{CO}(2-1)$ Channel Map in the concatenated data. The black ellipse at the bottom left of each panel represents the beam size. The contours in these maps indicate the 20σ level of the dust continuum, where $1\sigma = 17.5 \mu\text{Jy}/\text{beam}$.

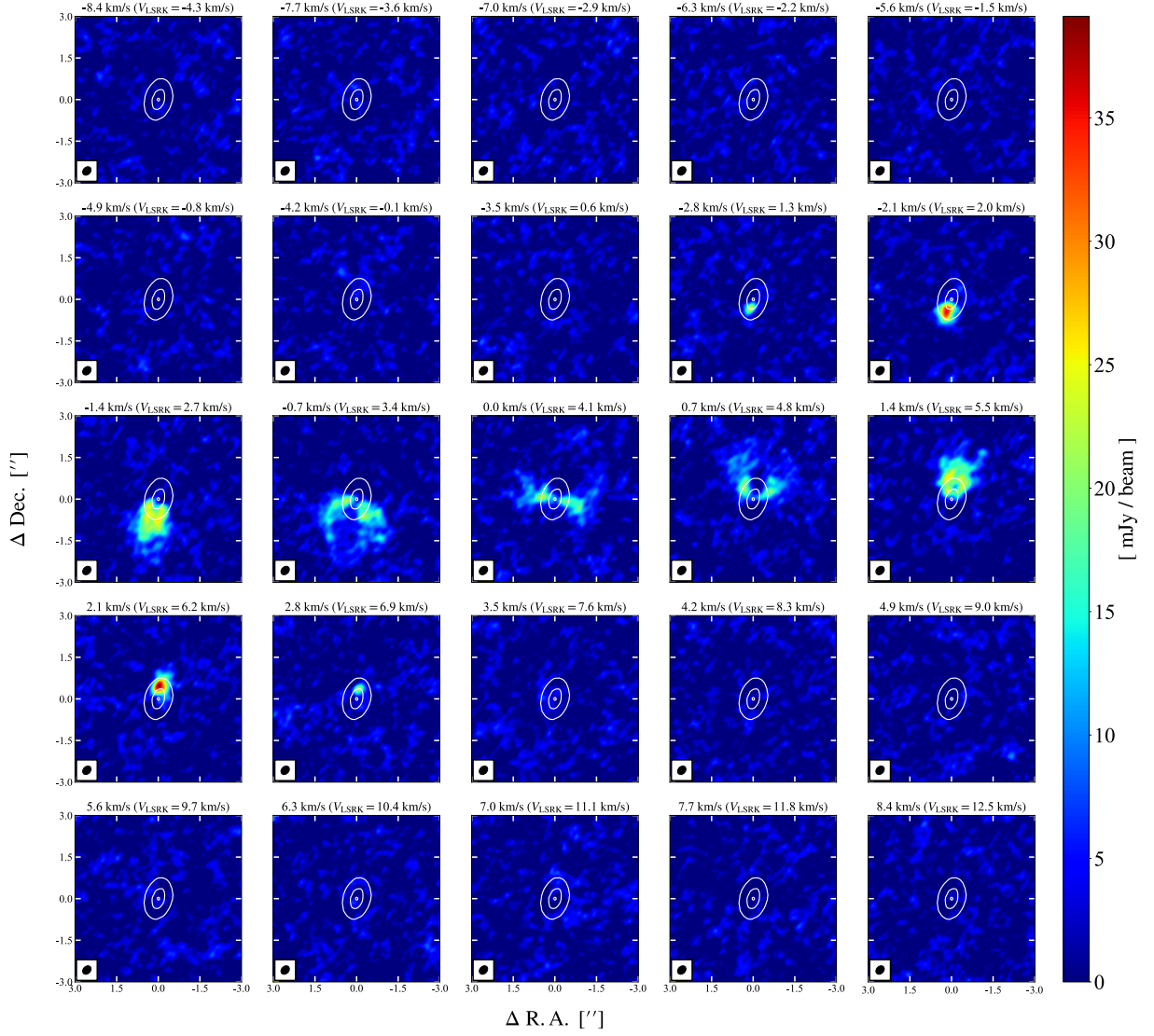


Figure G.3: $^{13}\text{CO}(2-1)$ Channel Map in the CC data. The black ellipse at the bottom left of each panel represents the beam size. The contours in these maps indicate the 20σ level of the dust continuum, where $1\sigma = 17.5 \mu\text{Jy}/\text{beam}$.

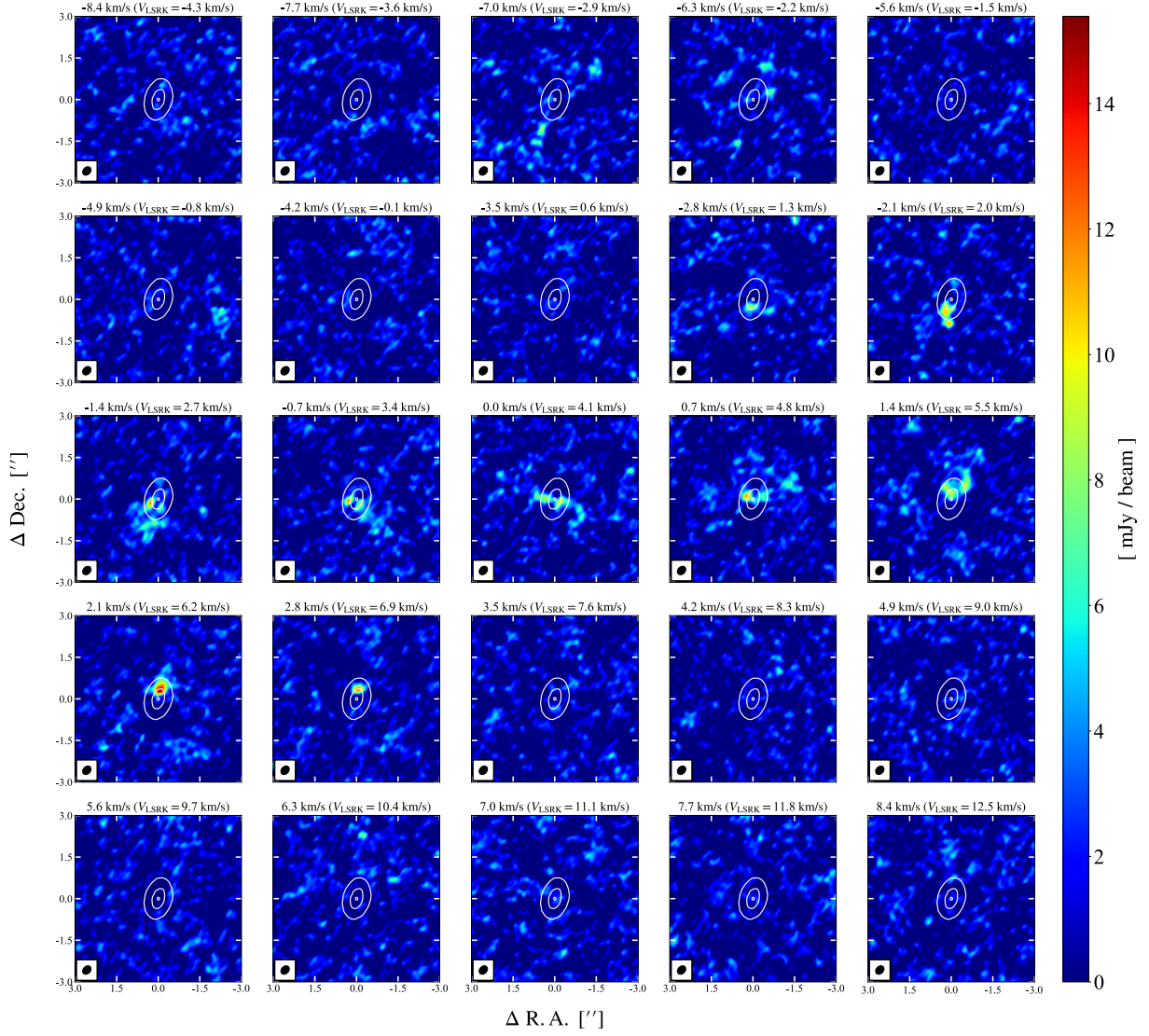


Figure G.4: $\text{C}^{18}\text{O}(2-1)$ Channel Map in the CC data. The black ellipse at the bottom left of each panel represents the beam size. The contours in these maps indicate the 20σ level of the dust continuum, where $1\sigma = 17.5 \mu\text{Jy}/\text{beam}$.

Appendix H

Visibility analysis of azimuthally symmetric disks

With reference to [Thompson et al. \(2017\)](#), I explain the visibility analysis of azimuthally symmetric disks.

H.1 Hankel transform

The Hankel transform of order zero is an integral transform equivalent to a two-dimensional Fourier transform with a radially symmetric integral kernel.

The Fourier transform between $f(x, y)$ and $F(u, v)$ is defined as follows:

$$F(u, v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) e^{-2\pi i(ux+vy)} dx dy, \quad (\text{H.1})$$

$$f(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(u, v) e^{2\pi i(ux+vy)} du dv. \quad (\text{H.2})$$

The transform can be converted to polar coordinates by defining $x = r \cos \theta$, $y = r \sin \theta$, $u = q \cos \phi$, and $v = q \sin \phi$, which is written

$$F(q, \phi) = \int_0^{2\pi} \int_0^{\infty} f(r, \theta) e^{-2\pi i r q (\theta - \phi)} r dr d\theta. \quad (\text{H.3})$$

If $f(r, \theta)$ is azimuthally symmetric (i.e. $f(r, \theta) = f(r)$), then

$$F(q, \phi) = \int_0^{\infty} f(r) r dr \int_0^{2\pi} e^{-2\pi i r q (\theta - \phi)} d\theta. \quad (\text{H.4})$$

Since the zeroth-order Bessel function is defined as

$$J_0(z) = \frac{1}{2\pi} \int_0^{2\pi} e^{-iz \cos \theta} d\theta, \quad (\text{H.5})$$

the Hankel transform can be written as

$$F(q) = 2\pi \int_0^\infty f(r) J_0(2\pi qr) r dr, \quad (\text{H.6})$$

$$f(r) = 2\pi \int_0^\infty F(q) J_0(2\pi qr) q dq. \quad (\text{H.7})$$

H.2 Azimuthally symmetric disks

If the disk has azimuthal symmetry (i.e., $I(l, m) = I(r)$, where $r = \sqrt{l^2 + m^2}$), the Fourier transform between the intensity and visibility becomes a Hankel transform as follows:

$$\mathcal{V}_{\text{real}}(q) = 2\pi \int_{-\infty}^\infty I(r) J_0(2\pi r q) r dr, \quad (\text{H.8})$$

$$I(r) = 2\pi \int_{-\infty}^\infty \mathcal{V}_{\text{real}}(q) J_0(2\pi r q) q dq, \quad (\text{H.9})$$

where $q = \sqrt{u^2 + v^2}$. $\mathcal{V}_{\text{real}}(q)$ is a real part of the visibility, and that's imaginary part is zero.

First, the considering a simple model, which is one of a uniform bright circular source of intensity I_0 and radius a , is useful for constructing of a more complicated disk model. Since

$$\int J_0(x) x dx = x J_1(x), \quad (\text{H.10})$$

$$\mathcal{V}_{\text{real}}(q) = \pi a^2 I_0 \frac{J_1(2\pi a q)}{\pi a q}. \quad (\text{H.11})$$

The visibility of an annulus of inner and outer radii a_1 and a_2 can be represented as the difference of two disk visibility functions

$$\mathcal{V}_{\text{real}}(q) = \pi a_2^2 I_0 \frac{J_1(2\pi a_2 q)}{\pi a_2 q} - \pi a_1^2 I_0 \frac{J_1(2\pi a_1 q)}{\pi a_1 q}. \quad (\text{H.12})$$

A useful model for the analysis of an azimuthally symmetric source might be a superposition of annuli in image space with intensities I_i and outer and inner radii of a_i and a_{i-1} . The inner radius of the innermost annuli is zero, so it is a disk. The visibility function is

$$\mathcal{V}_{\text{real}}(q) = \pi \sum_{i=0}^{n-1} (I_i - I_{i+1}) a_i^2 \frac{J_1(2\pi a_i q)}{\pi a_i q} + \pi I_n a_n^2 \frac{J_1(2\pi a_n q)}{\pi a_n q}. \quad (\text{H.13})$$

For the case of a uniform disk, all the I_i s are the same, i.e., I_0 , and the visibility is that of a uniform disk of radius a_n and intensity I_0 ,

$$\mathcal{V}_{\text{real}}(q) = \pi a_n^2 I_0 \frac{J_1(2\pi a_n q)}{\pi a_n q}, \quad (\text{H.14})$$

as expected.

Appendix I

Model fitting method

I.1 Bayesian modeling

θ is some unknown parameter vector of interest. We assume θ is random with some distribution, $p(\theta)$. This is the prior distribution of θ . There is also a data, $\mathbf{x}$, with the likelihood $p(\mathbf{x}|\theta)$. The joint distribution of θ and $\mathbf{x}$ is then given by

$$p(\theta, \mathbf{x}) = p(\theta)p(\mathbf{x}|\theta), \quad (\text{I.1})$$

and we can integrate the joint distribution to get the marginal distribution of $\mathbf{x}$, namely

$$p(\mathbf{x}) = \int_{\theta} p(\theta)p(\mathbf{x}|\theta)d\theta. \quad (\text{I.2})$$

We can compute the posterior distribution via Bayes's Theorem:

$$p(\theta|\mathbf{x}) = \frac{p(\theta)p(\mathbf{x}|\theta)}{p(\mathbf{x})} = \frac{p(\theta)p(\mathbf{x}|\theta)}{\int_{\theta} p(\theta)p(\mathbf{x}|\theta)d\theta}. \quad (\text{I.3})$$

Much of Bayesian analysis is concerned with understanding the posterior distribution $p(\theta|\mathbf{x})$. The posterior distribution is sometimes difficult to compute. Although in low dimension the calculation can be done without too much difficulties, it can become intractable in higher dimensions. In particular, the computing the marginal distribution $p(\mathbf{x})$ of Bayes's theorem is usually extremely difficult or impossible in practice. However, the normalization $p(\mathbf{x})$ is independent of θ once we have chosen the form of the generative model. This means that it is possible to sample from $p(\theta|\mathbf{x})$ without computing $p(\mathbf{x})$. This is important because $p(\mathbf{x})$ is generally very expensive to compute.

MCMC explained in next section and Bayesian modeling allow us to sample the posterior distribution without needing to know the marginal distribution.

I.2 Markov Chain Monte Carlo methods

With reference to [Hogg et al. \(2010\)](#), I explain the MCMC method.

First, the idea of Monte Carlo sampling is the following. The expectation value of a function of the model parameters $f(\theta)$ is

$$\langle f(\theta) \rangle = \int p(\theta|\mathbf{x}) f(\theta) d\theta \simeq \frac{1}{M} \sum_i^M f(\theta^i). \quad (\text{I.4})$$

Instead of trying to deal with intractable computations involving the posterior, we can get samples from this distribution (using only the not normalised part definition) and use these samples to compute various punctual statistics such as mean and variance.

MCMC is a procedure for generating a random walk in the parameter space that, over time, draws a representative set of samples from the distribution. Each point in a Markov chain $X(t_i) = \theta^i$ depends only on the position of the previous step $X(t_{i-1})$.

I.2.1 Metropolis Hastings algorithm

The Metropolis Hastings algorithm, a Markov chain Monte Carlo (MCMC) method, is one of the most popular techniques. The algorithm allows us to sample from an unknown distribution if we have known a function that is proportional to the probability density of the distribution we want to sample from.

We give the detailed balance condition for Markov chains written by

$$p(\theta)Q(\theta^*|\theta) = p(\theta^*)Q(\theta|\theta^*), \quad (\text{I.5})$$

where $p(\theta)$ is a target distribution, and $Q(\theta^*|\theta)$ is a transition probability going from θ to θ^* . If $p(\theta)$ satisfies this then $p(\theta)$ is a stationary distribution of the Markov chain. Moreover, using $\pi(\theta)$ to represent a function that is proportional to $p(\theta)$, we obtain

$$\frac{Q(\theta^*|\theta)}{Q(\theta|\theta^*)} = \frac{p(\theta^*)}{p(\theta)} = \frac{\pi(\theta^*)}{\pi(\theta)}. \quad (\text{I.6})$$

Here, we break up $Q(\theta^*|\theta)$ into two independent steps: a proposal distribution $q(\theta^*|\theta)$ and an acceptance distribution $A(\theta^*|\theta)$. Since they are independent, the transition probability is just the multiplication of the two:

$$Q(\theta^*|\theta) = q(\theta^*|\theta)A(\theta^*|\theta). \quad (\text{I.7})$$

Since $q(\theta^*|\theta)$ decides the next point we will potentially be sampling, it's important that it have the same support as the target distribution $p(\theta)$ (ergodicity condition). A typical choice here would be the normal distribution centered on the current state. Now given a fixed proposal distribution $q(\theta^*|\theta)$, we wish to find an $A(\theta^*|\theta)$ that matches. Re-writing Equation (I.6) and substituting in equation (I.7):

$$\frac{A(\theta^*|\theta)}{A(\theta|\theta^*)} = \frac{\pi(\theta^*)q(\theta|\theta^*)}{\pi(\theta)q(\theta^*|\theta)}. \quad (\text{I.8})$$

Although not obvious, a typical choice for A that satisfies this equation is

$$A(\theta^*|\theta) = \min \left[1, \frac{\pi(\theta^*)q(\theta|\theta^*)}{\pi(\theta)q(\theta^*|\theta)} \right]. \quad (\text{I.9})$$

Because the detailed balance is satisfied by the construction, the steady state of the generated Markov chain will be equal to the target distribution $p(\theta)$. The scheme for the Metropolis Hastings algorithm is presented in Algorithm 3.

Algorithm 3 Metropolis Hastings method

Initialize:

Set the initial parameter θ^0

Repeat:

- Generate uniform random number: $u \sim U(0, 1)$
- Generate a proposed value θ^* from proposal probability $q(\theta^*|\theta^i)$
- Compute an acceptance probability: $A = \min \left[1, \frac{\pi(\theta^*)q(\theta^i|\theta^*)}{\pi(\theta^i)q(\theta^*|\theta^i)} \right]$
- if $u < A$
 - $\theta^{i+1} = \theta^*$ (Accept the proposed value)
- otherwise
 - $\theta^{i+1} = \theta^i$ (Reject the proposed value)

Until:

Continue until sufficient number of samples $\{\theta^i\}$ are generated

For symmetric q (i.e. $q(\theta^*|\theta) = q(\theta|\theta^*)$), equation (I.9) becomes

$$A(\theta^*|\theta) = \min \left[1, \frac{\pi(\theta^*)q(\theta|\theta^*)}{\pi(\theta)q(\theta^*|\theta)} \right] = \min \left[1, \frac{\pi(\theta^*)}{\pi(\theta)} \right]. \quad (\text{I.10})$$

When the acceptance probability can be written by equation (I.10), the algorithm is called Metropolis method. Figure I.1 shows the MCMC sampling of two-dimensional parameter using Metropolis algorithm. The target distribution is the two-dimensional Gaussian distribution minus the normalization constants (figure I.1(a)). After setting the parameters, we reflect transition destinations candidate by rejecting and accepting based on the acceptance probability (figure I.1(b) and (c)). Figure I.1(4) shows the samples in step 10000, which are concentrated on center and have a distribution close to the target distribution.

The Metropolis Hastings algorithm converges (as $t \rightarrow \infty$) to a steady distribution of samples from the distribution but there are many algorithms with faster convergence and varying levels of implementation difficulty. Faster convergence is preferred because of the reduction of computational cost due to the smaller number of likelihood computations necessary to obtain the equivalent level of accuracy.

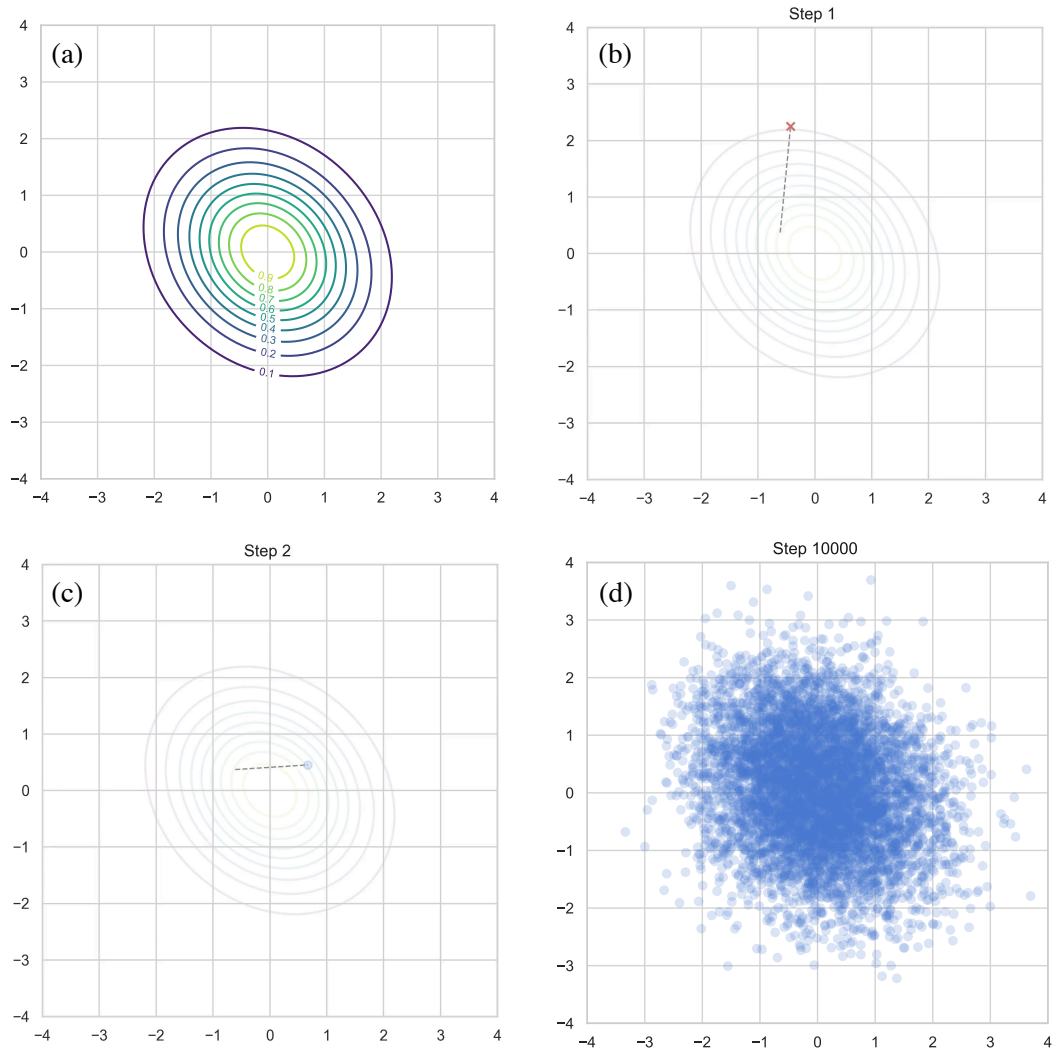


Figure I.1: Schematic figure of MCMC sampling from the two parameter distribution. The horizontal and vertical axes are the two parameters. (a): Non-normalized target distribution in the shape of the bivariate Gaussian is displayed by contours. (b): The red sample represents a rejected one. The dashed line represent the movement path from the current position to the next candidate position. (c): The blue sample represents an accepted one. (d): MCMC samples in step 10000. The samples are concentrated on center and have a distribution close to the target distribution shown in (a).

I.2.2 Stretch move algorithm

As mentioned in chapter 3.3, I performed the model fitting of the observed visibility by using `emcee` (Foreman-Mackey et al. 2013). The default move of `emcee` is the “stretch move”

ensemble method from Goodman & Weare (2010). This method involves simultaneously evolving an ensemble of K walkers $S = \theta^k$ where the proposal distribution for one walker k is based on the current positions of the $K - 1$ walkers in the complementary ensemble $S_{[k]} = \{\theta^i, \forall i \neq k\}$. Here, position refers to a vector in the N -dimensional, real-valued parameter space.

To update the position of a walker at position θ^k , a walker θ^i is drawn randomly from the remaining walkers $S_{[k]}$ and a new position is proposed:

$$\theta^k(t) \rightarrow \theta^* = \theta^i + Z[\theta^k(t) - \theta^i] \quad (\text{I.11})$$

where Z is a random variable drawn from a distribution $g(Z = z)$. It is clear that if g satisfies

$$g(z^{-1}) = zg(z), \quad (\text{I.12})$$

the proposal of equation (I.11) is symmetric. In this case, the chain will satisfy detailed balance if the proposal is accepted with probability

$$A = \min \left(1, Z^{N-1} \frac{p(\theta^*)}{p(\theta^k(t))} \right), \quad (\text{I.13})$$

where N is the dimension of the parameter space. This procedure is then repeated for each walker in the ensemble in series following the procedure shown in Algorithm 4.

Goodman & Weare (2010) advocate a particular form of $g(z)$, namely

$$g(z) = \begin{cases} \frac{1}{\sqrt{z}} & \text{if } z \in [\frac{1}{a}, a] \\ 0 & \text{otherwise} \end{cases} \quad (\text{I.14})$$

where a is an adjustable scale parameter that Goodman & Weare (2010) set to 2.

Algorithm 4 Stretch move

Initialize:

Set the initial parameter $\theta^k(0)$

Repeat:

- Draw a walker θ^i at random from the complementary ensemble $S_{[k]}(t)$
- Generate uniform random number: $u \sim U(0, 1)$
- Generate a proposed value θ^* from $\theta^i + Z[\theta^k(t) - \theta^i]$
- Compute an acceptance probability: $A = \min \left(1, Z^{N-1} \frac{p(\theta^*)}{p(\theta^k(t))} \right)$
- if $u < A$
 - $\theta^k(t+1) = \theta^*$ (Accept the proposed value)
- otherwise
 - $\theta^k(k+1) = \theta^k(t)$ (Reject the proposed value)

Until:

Continue until sufficient number of samples $\{\theta^k(t)\}$ are generated

I.3 Corner Plots of MCMC fitting results

Figure I.2 shows corner plot of the MCMC posteriors calculated in visibility fitting given the model presented as Equation (3.2). The plot shows the posterior sampling provided by the last 4000 steps of the 200 walkers chain.

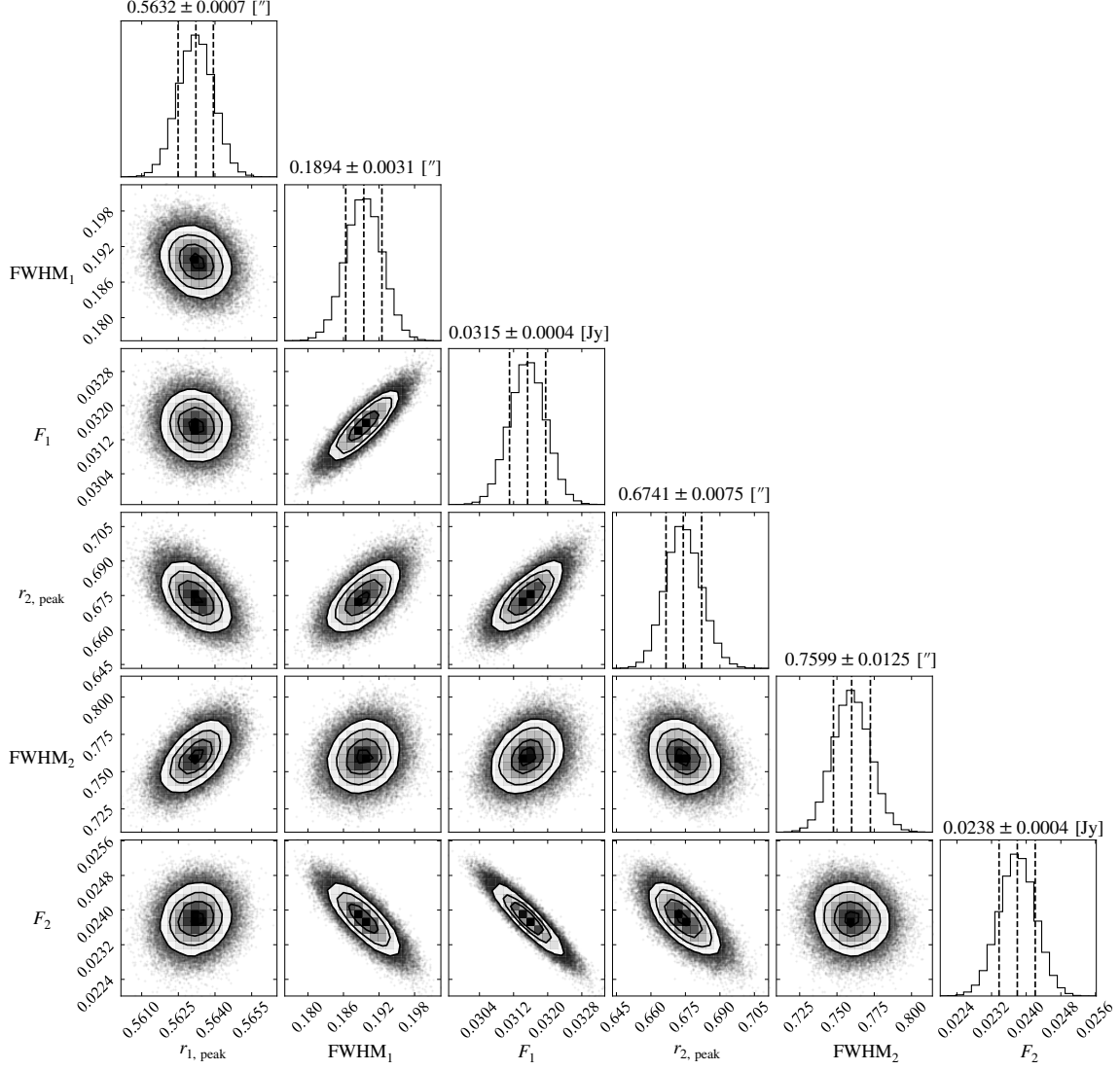


Figure I.2: Corner plot of MCMC results in visibility analysis. The median values and 1σ of the best-fit parameters are shown as vertical dashed lines.

Appendix J

Calculation of molecular column density

Calculating the optical depth τ_g using Equation (3.8), the molecular spectral line column density is expressed by the following equations (Mangum & Shirley 2015):

$$N_{\text{tot}} = \frac{3h}{8\pi^3 |\mu_{lu}|^2} \frac{Q_{\text{tot}}}{g_u} \exp\left(\frac{E_u}{kT_{\text{ex}}}\right) \left[\exp\left(\frac{h\nu}{kT_{\text{ex}}}\right) - 1 \right]^{-1} \int \tau_g dv \quad (\text{J.1})$$

$$g_u = 2J_u + 1 \quad (\text{J.2})$$

$$E_u = hBJ_u(J_u + 1) \quad (\text{J.3})$$

$$Q_{\text{tot}} \approx \frac{kT_g}{hB} + \frac{1}{3} \quad (\text{J.4})$$

$$|\mu_{lu}|^2 = \mu^2 S \quad (\text{J.5})$$

$$S = \frac{J_u^2}{J_u(2J_u + 1)} \quad (\text{J.6})$$

where μ , J_u , and B are the dipole moment, rotational quantum number of the line emission upper level, and rigid rotor rotational constant, respectively (parameters of each CO

isotopologue are shown in table [J.1](#)). The excitation temperature T_{ex} is equal to T_{g} in the LTE analysis. The gas column density is then calculated by

$$\Sigma_{\text{g}} = \frac{m_{\text{H}_2} N_{\text{tot}}}{X}, \quad (\text{J.7})$$

where $m_{\text{H}_2} (= 3.32 \times 10^{-24} \text{g})$ is the molecular mass of H_2 , and X is the molecular abundance ratio with H_2 .

In this study, the following equation was used to calculate the total flux of the $\text{C}^{18}\text{O}(2-1)$ line emission:

$$N_{\text{tot}}(\text{C}^{18}\text{O}) = \frac{3c^2}{16\pi^3 \Omega_S S \mu^2 \nu^3} \left(\frac{Q_{\text{rot}}}{g_{\text{u}}} \right) \exp \left(\frac{E_{\text{u}}}{kT} \right) \int S_{\nu} dv, \quad (\text{J.8})$$

where S_{ν} and Ω_S are the flux density and beam size, respectively.

Table J.1: Physical parameters of CO isotopologue

	$^{12}\text{CO}(2-1)$	$^{13}\text{CO}(2-1)$	$\text{C}^{18}\text{O}(2-1)$
μ [10^{-18} esu cm]	0.110	0.110	0.1098
J_{u}	2	2	2
B [MHz]	57635.96	55101.01	54891.42
abundance ratio with H_2	10^{-4}	1.67×10^{-6}	1.79×10^{-7}

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