

Spirals and vertical motions in the planet-forming disk around HD 100546

A multiline study of its gas kinematics

Lisa Wölfer^{1,2,*}, Andrés F. Izquierdo^{2,3,4,**}, Alice Booth^{2,5}, Stefano Facchini⁶, Richard Teague¹,
Ewine F. van Dishoeck^{2,7}, Teresa Paneque-Carreño^{2,4,8}, and Bill Dent⁹

¹ Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

² Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands

³ Department of Astronomy, University of Florida, Gainesville, FL 32611, USA

⁴ European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching bei München, Germany

⁵ Center for Astrophysics | Harvard & Smithsonian, 60 Garden St., Cambridge, MA 02138, USA

⁶ Dipartimento di Fisica, Università degli Studi di Milano, Via Celoria 16, 20133 Milano, Italy

⁷ Max-Planck-Institut für extraterrestrische Physik, Gießenbachstr. 1, 85748 Garching bei München, Germany

⁸ Department of Astronomy, University of Michigan, 323 West Hall, 1085 S. University Avenue, Ann Arbor, MI 48109, USA

⁹ Joint ALMA Observatory, Avenida Alonso de Córdova 3107, Vitacura 7630355, Santiago, Chile

Received 20 March 2023 / Accepted 12 December 2025

ABSTRACT

Context. The disk around the Herbig star HD 100546 represents a particularly interesting target for the study of dynamical planet–disk interactions, as various features observed in both the dust and gas provide direct and indirect evidence for ongoing planet formation.

Aims. In this work, we aim to characterize the gas kinematics of five molecular CO emission lines (¹²CO 7–6, ¹²CO 3–2, ¹²CO 2–1, ¹³CO 2–1, C¹⁸O 2–1), observed with ALMA in HD 100546, to reveal deviations from Keplerian rotation, along with substructures in the peak intensity and line width.

Methods. For our analysis, we fit the molecular intensity channels with the DISCMINER package to model the line profiles and extract observables such as the centroid velocity, peak intensity, and line width. In addition to fitting the full cube, we also conducted runs where the blue- and redshifted sides were modeled separately to search for possible asymmetries.

Results. Our analysis reveals prominent kinematical spiral features in all five lines on large scales of the disk and we were able to reproduce their morphology with both a linear and logarithmic spiral. In ¹²CO 2–1, spirals are also seen in the peak intensity residuals, while the line width residuals exhibit a prominent ring of enhanced line widths around 125–330 au. The models further show that the emission from the redshifted side may originate from higher disk layers than that from the blueshifted side, with the asymmetry being especially pronounced for ¹²CO 7–6.

Conclusions. The pitch angles of the spirals are consistent with those driven by an embedded companion inside of 50 au, suggesting a dynamical mechanism rather than gravitational instabilities. Furthermore, we found indications of a companion around 90–150 au, where tentative dips are present in the radial profiles of the integrated intensity of ¹³CO and C¹⁸O 2–1 and pressure minima are observed in the azimuthal velocities. For the first time, we also detected downward vertical flows in this region, which coincide with the observed dust gap. The asymmetry in the emission heights could be a result of infall from the disk’s environment. Another explanation could be the presence of a warped inner disk casting a shadow onto one side of the disk.

Key words. accretion, accretion disks – protoplanetary disks – planet-disk interactions – stars: individual: HD 100546 – submillimeter: planetary systems

1. Introduction

To understand planet formation and the diversity of developed planetary systems such as our own, it is crucial to study the early stages of evolution, when (proto) planets are still embedded in their birthplaces (so-called protoplanetary or planet-forming disks). These disks are not static objects, but they evolve and eventually disperse over time with the evolutionary processes not only shaping the disk’s appearance, but also influencing (and placing a limit on) planet formation mechanisms. Conversely, planets interact with their environment and impact

disk evolution. They are also expected to alter their host disk’s structure, for example, in terms of density, temperature, or velocity. Even though such young embedded planets could be hidden from the direct eye of our telescopes, their planet–disk interactions still create signatures that are observable at a given planetary mass and location.

Over the last decade, high-angular-resolution observations of the dust and gas in protoplanetary disks with the Atacama Large Millimeter/submillimeter Array (ALMA; [ALMA Partnership 2015](#)), the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE; [Beuzit et al. 2019](#)), or the Gemini Planet Imager (GPI; [Macintosh et al. 2014](#)) have enabled scientists to search for such signposts of planet-disk interactions. These observations have revealed the ubiquitous nature of a variety of

* Corresponding author: lwoelfer@mit.edu

** NASA Hubble Fellowship Program Sagan Fellow

substructures such as gaps, cavities, rings, spiral arms, azimuthal asymmetries, and shadows in both the dust and the gas components (e.g., Bae et al. 2023; Benisty et al. 2023). To interpret the origin of these substructures, it is necessary to understand how frequent they are, as well as to discern possible patterns they follow and to search for differences or similarities between different star-disk system morphologies.

While various mechanisms such as photoevaporation (e.g., Owen et al. 2011; Picogna et al. 2019), gravitational instabilities (e.g., Kratter & Lodato 2016), magnetorotational instabilities (e.g., Flock et al. 2015, 2017; Riols & Lesur 2019), zonal flows (e.g., Uribe et al. 2015), or compositional baroclinic instabilities (e.g., Klahr & Bodenheimer 2004) have been invoked to explain the observations, at least some of the substructures are expected to be linked to the presence of (massive) planets (Lin & Papaloizou 1979; Zhang et al. 2018). In this context, the so-called transition disks represent a particularly interesting subgroup of young stellar objects (YSOs). These disks are marked by inner regions depleted in dust and gas (e.g., Espaillat et al. 2014; Ercolano & Pascucci 2017), which were originally identified through a lack of infrared (IR) excess in their spectral energy distribution (SED; Strom et al. 1989). While they might represent an intermediate (transitioning) state between an optically thick (full) disk and disk dispersal, dynamical clearing by a massive companion represents an alternative explanation. At least some of the cavities, and particularly the very deep ones (e.g., van der Marel et al. 2016), are expected to be the result of such processes rather than representing an evolutionary state. Therefore, transition disks represent ideal laboratories for probing disk evolution as well as planet formation models, potentially enabling us to capture planet formation in action.

Ultimately, only a direct detection can confirm the link between the observed disk substructures and an embedded planet. However, the dense and opaque environment of these young planets makes such a task difficult and feasible only for the very massive, bright planets that are less affected by dust extinction (Sanchis et al. 2020). To date, the only robust detections of forming planets (of several M_J) and their circumplanetary disks have been obtained for the PDS 70 system (Keppler et al. 2018; Haffert et al. 2019; Benisty et al. 2021), as well as, more recently, for the WISPIT 2 system (van Capelleveen et al. 2025; Close et al. 2025).

The challenge of direct detections and our growing understanding of how planets interact with their host disk have triggered the development of other, indirect detection techniques. One promising method is to study the velocity field of the rotating gas, observed through molecular line emission, to search for deviations from Keplerian rotation (Perez et al. 2015; Pinte et al. 2023). Identifying such variations in the kinematics can be used to probe the local pressure gradient and to characterize the shape of the perturbation. Several ALMA observations in recent years have reported both localized and extended kinematical deviations, which might be linked to the presence of planets: so-called kink-features have been detected by Pinte et al. (2018b, 2019) in HD 163296 and HD 97048, while a Doppler flip was reported in the HD 100546 disk by Casassus & Pérez (2019). Teague et al. (2018) and Teague et al. (2019a) studied the rotation profile of HD 163296, finding perturbations and significant meridional flows that point toward embedded planets. Izquierdo et al. (2022) applied the DISCMINER tool (Izquierdo et al. 2021) to the same disk. This is a channel map-fitting package with the capacity to model the upper and lower disk surfaces simultaneously and to identify localized velocity perturbations in both radius and azimuth. As a result, they found strong

indications for two embedded planets. Extended spiral structures are observed in the kinematical residuals of TW Hya (Teague et al. 2019b, 2022a), HD 100453 (Rosotti et al. 2020), HD 135344B (Casassus et al. 2021), CQ Tau (Wölfer et al. 2021), HD 163296 and MWC 480 (Teague et al. 2021), J1604 (Stadler et al. 2023), and HD 142527 by Garg et al. (2021). Moreover, the exoALMA large program conducted a comprehensive kinematical study of 15 disks to search for signatures of young embedded planets (Teague et al. 2025), revealing complex kinematic patterns in most disks and signatures consistent with a planet in six disks (Pinte et al. 2025).

Aside from the kinematics, it is also interesting to study the patterns in the peak intensity and line widths, which are both shaped by the presence of companions and can be used to trace density substructures, vertical motions, or turbulence. Planets can create density waves that result in an increased surface density and thus higher opacity, moving the $\tau = 1$ layer to a higher altitude where the temperature is generally higher (Phuong et al. 2020a,b). This leads to spiral substructures in the gas brightness temperature. Thermal spiral features were reported for the case of TW Hya by Teague et al. (2019b) and CQ Tau by Wölfer et al. (2021). These observations could be explained by the models of Muley et al. (2021), who investigated the temperature structure in planet-driven spiral arms. Wölfer et al. (2023) studied the gas brightness temperature (and kinematics) of a sample of 36 transition disks, finding significant substructures such as spirals in eight sources. Around the orbit of a massive planet, turbulent motions are triggered and expected to result in enhanced line widths. Izquierdo et al. (2022) indeed observed an enhancement of line widths around the gas gap at 88 au in HD 163296, which further supports their findings of a planet candidate at 94 au. Enhanced line widths are also found in HD 135344B by Casassus et al. (2021).

In this work, we present a multiline study of CO gas emission in the transitional disk HD 100546 one particularly interesting target to study planet-disk interactions. The young Herbig Be star, located at ~ 110 pc from the Earth (Gaia Collaboration 2018), is surrounded by a massive disk spanning several hundreds of au and showing various indications of ongoing planet formation, as described in the next section. For our analysis, we applied the DISCMINER package presented in Izquierdo et al. (2021) to archival B6 (^{12}CO 2–1, ^{13}CO 2–1, C^{18}O 2–1), B7 (^{12}CO 3–2), and B10 (^{12}CO 7–6) data to search for perturbations in the velocities, intensities, and line widths (possibly linked to embedded planets) and to obtain the vertical structure of the disk. Probing different layers of the disk with various isotopologues or transitions of the same molecule (as done in this study) or different molecules (e.g., Paneque-Carreño et al. 2023) is crucial to our understanding of how the observed substructures vary and how they can help us to access their formation mechanism (e.g., Pinte et al. 2018a; Law et al. 2021). We describe the source and observations in Sect. 2. Our modeling approach is detailed in Sect. 3 and the results are presented in Sect. 4. We discuss our results in Sect. 5 and present our conclusions in Sect. 6.

2. Observations

2.1. The HD 100546 system

In Fig. 1, we show the possible morphology of the HD 100546 system further described in the following. Observations of a compact source (in the L' band) have been interpreted as direct evidence of an embedded companion in the outer disk at ~ 53 au (Quanz et al. 2013, 2015; Currie et al. 2015), also known as the

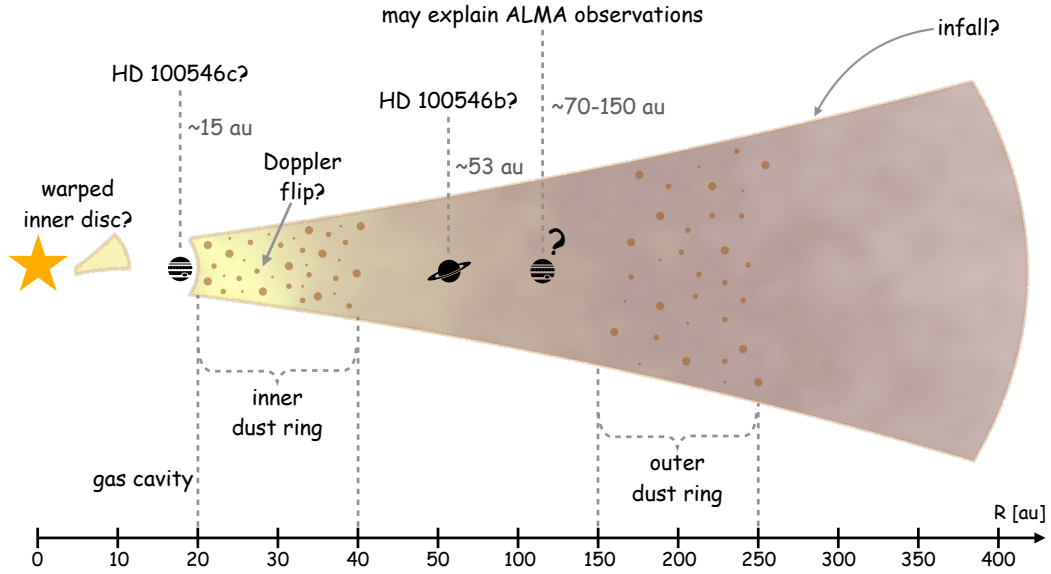


Fig. 1. Possible morphology of the HD 100546 system. Substructures such as the dust rings have been observed, while the planet candidates have been proposed to explain the observations. The two planets suggested in the dust gap may refer to the same object for which the actual location remains undetermined.

giant planet candidate HD 100546 b. Subsequent *K*-band observations, however, have revealed a faint extended emission around the same location (Boccaletti et al. 2013) and, thus, the planetary origin of the observed feature yet needs to be confirmed. Another giant planet, HD 100546 c, might be located at ~ 14 au, just inside the dust cavity. First postulated by Acke & van den Ancker (2006) and later identified as a point source in near-IR (NIR) scattered light data taken with GPI (Currie et al. 2015), the detection of HD 100546 c has been debated in the literature (e.g., Follette et al. 2017; Currie et al. 2017). The presence of the planet is supported by studies on the time variations of ro-vibrational CO emission lines (Brittain et al. 2009, 2013, 2014, 2019), tracing the inner edge of the disk. These observations showed an excess of CO P(26) line emission between 2003 and 2013 (consistent with an orbiting planet) that disappeared in 2017, as the possible planet moved behind the near side of the inner rim of the outer disk. Assuming a common origin, the feature observed in the scattered light is expected to disappear as well and recent observations with VLT/SPHERE do indeed lack a detection (Sissa et al. 2018).

Alongside the direct measurements, the HD 100546 disk also exhibits a number of indirect evidence for planet-disk interactions. The scattered light images are marked by spiral structures (e.g., Garufi et al. 2016; Follette et al. 2017) and the millimeter (mm) continuum, well studied with ALMA, reveals a large inner cavity ($\lesssim 20$ au) with the dust being concentrated into two prominent rings between 20–40 au and 150–250 au (e.g., Walsh et al. 2014; Pineda et al. 2019; Fedele et al. 2021). Models show that these substructures are consistent with two giant planets orbiting at locations of 10–15 au and 70–150 au (Pinilla et al. 2015; Fedele et al. 2021; Pyerin et al. 2021). In addition to the dust, the gas disk of HD 100546 has been studied through a range of molecular tracers. ALMA observations of the CO isotopologues are numerous and show that the disk is much more extended in the gas than in the dust (e.g., Walsh et al. 2014; Miley et al. 2019).

The ^{12}CO emission revealed non-Keplerian features in the kinematics that may be a signpost of ongoing planet formation: Walsh et al. (2017) found asymmetries that could be explained by a warped inner disk; however, this assumption stands in

contrast to SPHERE observations of the disk by Garufi et al. (2016), who suggested radial flows mediated by planets as an alternative explanation. A warp was also proposed by Panić et al. (2010) to account for asymmetric line observations (^{12}CO $J = 6-5$ and $J = 3-2$) from APEX. As mentioned before, Casassus & Pérez (2019) detected a Doppler flip at ~ 28 au, which is in agreement with the spiral wake created by a planet and coincides with a fine ridge in the mm continuum, suggesting a complex dynamical scenario. The Doppler flip is confirmed by Casassus et al. (2022), with the blueshifted side of the flip disappearing when vertical and radial flows are taken into account. The authors propose an embedded outflow, launched by a companion of several M_{Earth} , as a possible explanation. This could explain the observations by Booth et al. (2018), who detected non-Keplerian features in the blueshifted side of SO line emission that may be tracing a disk wind, a warped disk, or an accretion shock onto a CPD. Follow-up observations by Booth et al. (2023) support that the azimuthal SO asymmetry is indeed tracing an embedded planet. Another interpretation of the Doppler flip as being the kinematic counterpart of the NIR spiral was proposed by Norfolk et al. (2022). Pérez et al. (2020) analyzed the wiggles seen in the velocity channels of ^{12}CO , ^{13}CO , and C^{18}O . They found that the most pronounced wiggle in ^{12}CO resembles the imprint of an embedded massive planet. The strength of the wiggles decreases for ^{13}CO and C^{18}O and, thus, with disk height, suggesting that the perturbed flow is associated with vertical motions in the disk surface. As shown by Izquierdo et al. (2021), such kink-like features can also be caused by a gap or density substructures (rather than a planet) and caution ought to be exercised in interpreting these perturbations.

HD 100546 is known to still be embedded in a faint envelope (Grady et al. 2001; Ardila et al. 2007), reaching out to about 1000 au. Such an envelope may be linked to secondary accretion events due to infalling material onto the disk, which is often accompanied by arc-shaped structures, as observed in HD 100546 (Dullemond et al. 2019). Asymmetric accretion from an envelope can result in a tilt of the disk (Thies et al. 2011) or the formation of vortices (Bae et al. 2015). It could also drive spirals due to accretion shocks that propagate the disk

Table 1. Observational properties of the ALMA datasets used in this work.

Project ID	Date	Baselines (m)	Int. time (min)	Central freq. (GHz)	Bandwidth (MHz)	$\Delta\nu$ (km s ⁻¹)	Ang. res. ($''$)	LAS ($''$)
2011.0.00863.S Cycle 0	18 Nov 2012	21–375	12	345.798	469	0.211	0.57	6.66
2015.1.00806.S Cycle 3	02 Dec 2015	17–10 800	30	345.796	469	0.212	0.035	0.471
2016.1.00344.S Cycle 4	Oct 2016 – Sep 2017	19–12 200	35, 117	230.538 220.399 219.560	117	0.158	0.183, 0.037	1.983, 0.745
2018.1.00141.S Cycle 6	14 Apr 2019	15–780	28	807.499	1875	0.181	0.165	2.007

(Lesur et al. 2015; Hennebelle et al. 2017). Spirals have been observed in HD 100546 in both the optical (Grady et al. 2001; Ardila et al. 2007) and the NIR (Avenhaus et al. 2014; Sissa et al. 2018). In this paper, we aim to shed some additional light onto the observed kinematical deviations by analyzing different CO tracers in datasets that cover both the inner and outer disk with the channel map-fitting package DISCMINER.

2.2. ALMA observations

The molecular line emission of the disk around HD 100546 has been observed with ALMA in several frequency bands. In this work, we made use of the datasets 2011.0.00863.S (PI: C. Walsh; Walsh et al. 2014), 2015.1.00806.S (PI: J. Pineda; Pineda et al. 2019), 2016.1.00344.S (PI: S. Pérez; Pérez et al. 2020), and 2018.1.00141.S (PI: B. Dent), which cover CO isotopologues in Bands 6, 7, and 10. Their properties are summarized in Table 1. For all of the datasets, we started with the archival pipeline-calibrated data and performed further reductions using CASA version 5.7.0 (McMullin et al. 2007).

The Band 6 data of the ¹²CO, ¹³CO, and C¹⁸O $J = 2-1$ line were taken in two configurations during Cycle 4: an extended (C40-9) as well as a compact configuration (C40-6) with the same spectral setting. We self-calibrated and combined these data following the same procedure as described in Czekala et al. (2021): we self-calibrated the short-baseline data first and then combined it with the calibrated long-baseline data, after ensuring that the datasets share a common phase centre. Afterwards, we applied further iterations of self-calibration, in both phase and amplitude.

For the combination of the Band 7 data, we took a slightly different approach as the datasets do not share a significant overlap in the spectral settings (aside from both targeting the ¹²CO $J = 3-2$ line). The long-baseline data taken during Cycle 3 have insufficient short baselines to properly recover spatial scales $>1''$. To improve this, we combined the data with observations from Cycle 0. We note that since these observations were taken in different cycles and taken with different settings, they are not optimal for data combination. Each dataset was first self-calibrated (phase and amplitude) individually. The Cycle 0 data were initially pipeline calibrated in CASA version 3.4 and therefore we applied the CASA task `statwt` to these data to account for the change in the visibility weight initialization and calibration across different CASA versions <4.3 ¹. The self-calibrated

Table 2. Characteristics of the non-JvM corrected data analyzed in this work.

Line	$\Delta\nu$ (km s ⁻¹)	Beam ($''$)	RMS (mJy beam ⁻¹)	Line peak
¹² CO 2–1	0.17	0.10×0.08	1.9	70.9
¹³ CO 2–1	0.17	0.10×0.08	1.9	30.6
C ¹⁸ O 2–1	0.17	0.10×0.08	1.6	21.4
¹² CO 3–2	0.21	0.12×0.09	8.8	215.8
¹² CO 7–6	0.185	0.23×0.17	87.6	4207.5

datasets were then combined after ensuring they share a common phase centre. For the Band 10 data, no self-calibration was performed due to a lack of the signal-to-noise-ratio (S/N).

The continuum was subtracted using the `uvcontsub` task, flagging channels that contained line emission. We then imaged the lines with `tcLEAN` for both the continuum-subtracted and non-subtracted datasets. In the cleaning process, we used a Briggs robust weighting of +0.5, the “multiscale” deconvolver, and a Keplerian mask². A slight `uv-taper` was applied in all Bands in order to improve the S/N in the images. The properties of the final images are summarized in Table 2. As high spectral resolution is essential to study kinematics, we imaged the lines with the best possible spectral resolution. However, to ease the comparison between the lines, we also made images for the same velocity resolution, given by the lowest resolution among the datasets (B7, 210 m s⁻¹). We conducted our full analysis on both the image cubes described above and on image cubes with artificially reduced noise levels using the so-called JvM correction (Jorsater & van Moorsel 1995; Czekala et al. 2021). In the following, we only present the results for the non-corrected cubes, while the JvM-corrected data are included in Appendix G. Our results are consistent among both datasets. In Figs. A.1 and A.2, we show a comparison between the final images of the individual and combined datasets for the Band 7 ¹²CO $J = 3-2$ line, where it becomes very clear that the inclusion of the shorter baseline data significantly improves the recovery of flux and image fidelity in the outer disk.

2.3. Observational results

In Fig. 2, we present the continuum-subtracted intensity channels of the five CO lines in steps of three from the central channel and

¹ https://casadocs.readthedocs.io/en/stable/notebooks/data_weights.html

² https://github.com/richteague/keplerian_mask

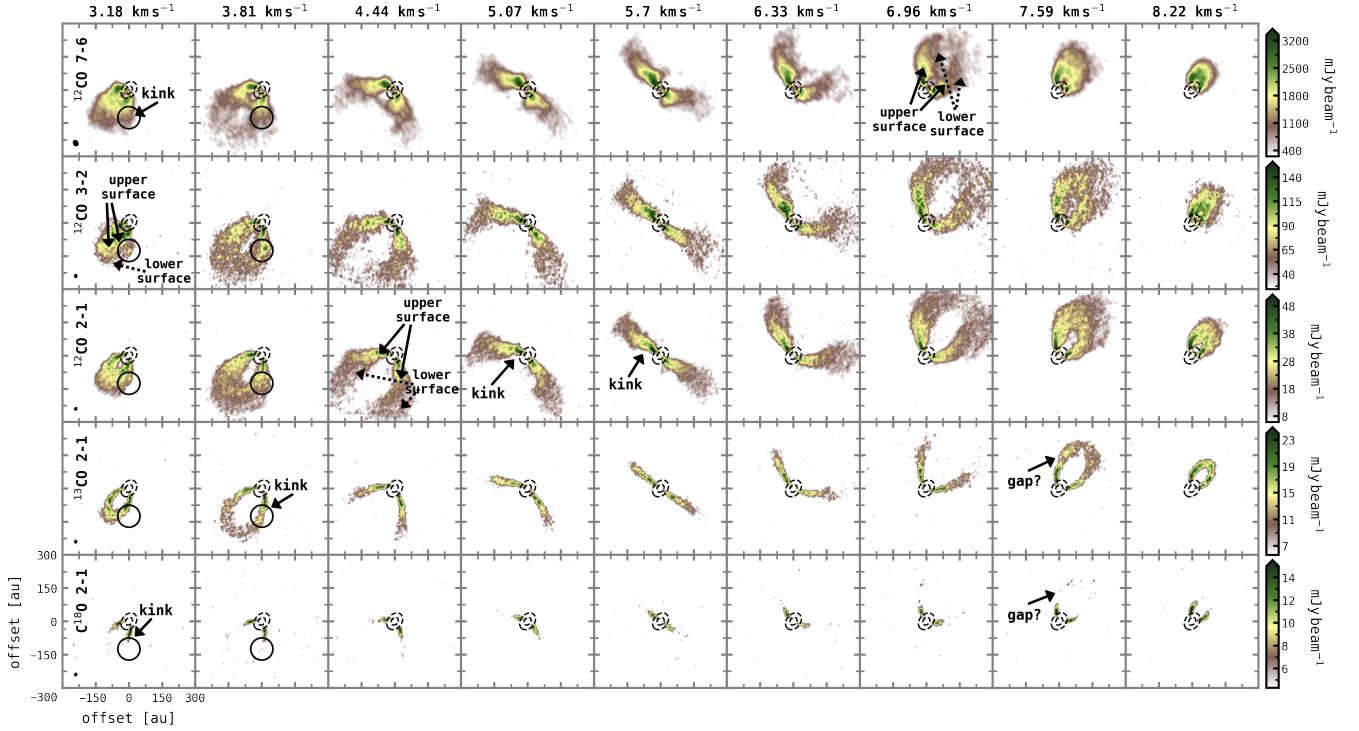


Fig. 2. Examples of the intensity channels of the five CO lines, shown in steps of three from the central channel and for a velocity resolution of 210 m s^{-1} . The inner ring of the mm continuum is overlaid as dashed contours. The upper and lower disk surface are annotated in some channels as well as a potential gap and velocity kinks. A localized feature is seen in some of the channels within the solid circle. The beam of the observation is indicated in the bottom left corner of the first column panels. The channel maps are masked below 3σ .

for the same channel spacing of 210 m s^{-1} . The inner continuum ring is overlaid as dashed contours, showing that the gas disk is much more extended than the dust disk. As seen in the first three rows of Fig. 2, the ^{12}CO data appear elevated with the lower surface of the disk being at least partly visible. The other two isotopologues, shown in the bottom two rows, on the other hand, appear rather flat and the lower surface cannot be distinguished. This suggests that the emission from these molecules comes, as generally expected (Law et al. 2021), from lower heights in the disk located closer to the midplane. For these rarer isotopologues, any line wing emission may be missing due to sensitivity effects.

In the first two channels of the ^{12}CO 3–2 data, a bright spot is visible at a separation of $\sim 100 \text{ au}$ to the south of the central star, highlighted by the solid black circle in Figs. 2 and A.1. As those data represent a combination of ALMA Cycle 0 and Cycle 3 data, both time variations and a difference in the observational setups may lead to imaging artifacts. It could also be the result of a projection effect. However, looking at the other lines, a similar (yet much weaker) spot is present in the ^{12}CO 2–1 data and a wiggle or break can be discerned in the corresponding ^{12}CO 7–6 and ^{13}CO 2–1 channels around this area. Altogether, this points toward the localized feature being real, but higher sensitivity data including both the long and the short baselines in the same observational setup are needed to support this claim. Continuum subtraction can be ruled out as a cause for the substructure as the continuum ring is located much closer to the star. A comparison of the combined data with the long- and short-baseline data is included in Appendix A.

The channels of ^{12}CO 7–6 appear to be very asymmetric, with the iso-velocity curves appearing to be twisted in the centre with the two sides bending in opposite directions. As the emission is expected to come from the highest layers of the disk, this

asymmetry possibly results from interactions with material surrounding the disk, but could also point toward misaligned disk regions (e.g., Walsh et al. 2017; Facchini et al. 2018). Furthermore, the northeast side of the disk appears to be brighter than the southwest side of the disk. The ^{13}CO and C^{18}O data show tentative signs of an outer intensity gap in the disk, becoming most prominent for the 7.59 km s^{-1} channel; however, higher sensitivity data are needed to confirm its presence. As mentioned in previous works (Pérez et al. 2020), several of the velocity channels are marked by wiggles or kink-like features in their profile, some of which are annotated in Fig. 2.

In Fig. 3, we show the integrated and peak intensity maps alongside the kinematics for all five lines. These maps were computed with the BETTERMOMENTS package (Teague & Foreman-Mackey 2018) and in case of the peak intensity converted to units of Kelvin with the Planck law. While the intensity maps were obtained with the standard moment 0 and 8 implementations, respectively, the kinematics were derived with the quadratic method. In this approach, a quadratic function is fitted to the brightest pixel in the spectrum as well as the two neighboring pixels to find the centroid of the line in pixel coordinates. We note that for optically thick lines, continuum subtraction can remove part of the line emission and artificially lower the peak intensity, since part of the underlying continuum gets absorbed (e.g., Weaver et al. 2018; Rosotti et al. 2021; Bosman et al. 2021). While we did not apply any masking in the computation of the peak intensity maps, a Keplerian mask was included in the computation of the integrated intensity. For the kinematics, we selected a masking for regions below a certain S/N to reduce the noise at the disk’s edge (between 4–5).

As seen in the intensity maps, an inner gas cavity ($< 20 \text{ au}$) is present in all isotopologues and lines. At the same location as in the channel maps, a localized (albeit weak) spot is seen in

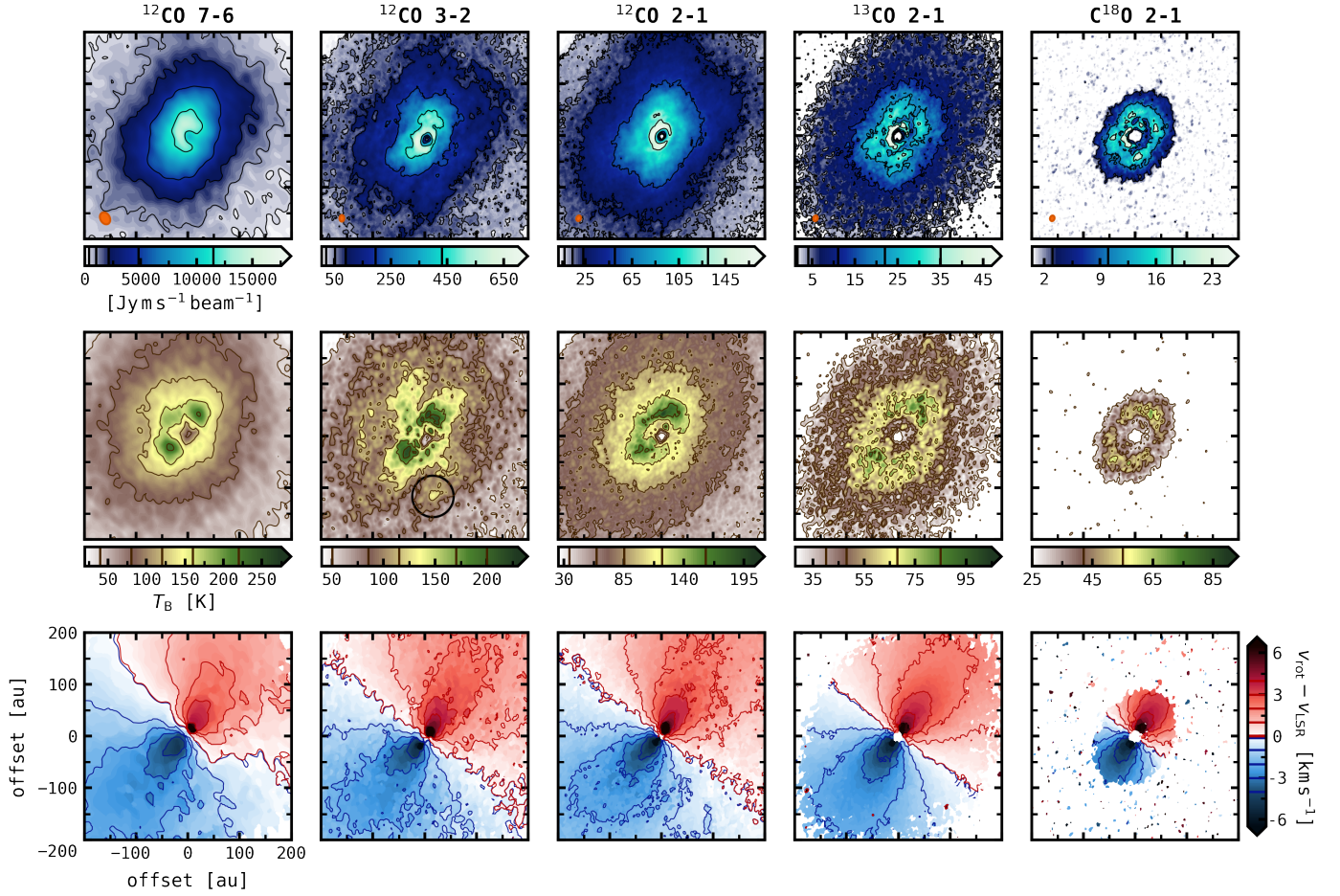


Fig. 3. Integrated intensity (top), peak intensity (middle), and line-of-sight velocity (bottom) of the five CO lines studied here. A localized feature is seen in ^{12}CO 3–2 around 125 au, marked by the solid circle. Some contours are overlaid and their levels are indicated in the color bars. The beam of the observation is shown in the bottom left corner of the first-row panels. The integrated intensity maps are masked at 3σ , the peak intensity maps at 5σ .

the peak intensity of ^{12}CO 3–2 (black circle in Figs. 3 and A.2), the other lines are lacking a similar feature at this location. In general, the ^{12}CO 3–2 intensities appear to be very asymmetric, with a cross-like (or possibly spiral-like) structure extending toward the north and south. Again, caution should be exercised with regard to these substructures, as artifacts may have been introduced through the combination of datasets. In Fig. A.2, we compare the intensity and kinematical maps for the different ^{12}CO 3–2 datasets. Even though the long-baseline observation might be lacking flux in some regions, the cross-like structure is also present in the short-baseline data, pointing toward a real substructure and suggesting that no strong artifacts have been introduced in the imaging process. However, with three years having passed between the two observations, some time variations cannot be ruled out. It is puzzling that no similar structures are found in the ^{12}CO 2–1 and ^{12}CO 7–6 data. While the lack of features in ^{12}CO 2–1 may be explained by temperature effects with the substructures becoming visible only at a certain height above the midplane, a similar pattern would at least be expected in ^{12}CO 7–6, which traces even higher disk layers. Interactions with material from the environment of the disk could, however, wash out substructures. Moreover, ^{12}CO 7–6 may be lacking flux in the outer disk regions. To get to the bottom of these peculiar substructures, it is crucial to obtain higher sensitivity data with a similar observational setup in the future.

At first glance, the kinematics generally suggest an only mildly elevated disk: despite an inclination of $\sim 40^\circ$ only slight contributions from the back side of the disk are visible in ^{12}CO and no contributions are seen in ^{13}CO and C^{18}O . In the ^{12}CO 7–6 kinematics, the central velocity seems to be off by a few 100 m s^{-1} from the systemic velocity of the source at 5.7 km s^{-1} . This is also seen in the according channel map in Fig. 2 which appears “S-shaped” as the south wing is bent upwards compared to the north wing. The central channel of the other lines on the other hand appears more symmetric. Assuming that ^{12}CO 7–6 emission comes from a higher disk layer, the disk’s surface may be distorted due to interactions with material from the environment. We analyze the kinematics in further detail in Sect. 3.

Figure 4 presents normalized, azimuthally averaged radial profiles of the integrated intensity for the lines of this analysis and the continuum emission. These profiles were obtained with the GOFISH package (Teague 2019) by shifting and stacking all line spectra to increase the S/N. This approach is based on the assumption that the disk is symmetric and Keplerian, which does not necessarily hold. Therefore, we compared the profiles to those obtained from simply azimuthally averaging the moment 0 maps, yielding similar results. By default, the widths of the annuli in the GOFISH package are given as one-fourth of the beam major axis. For the deprojection, we assume a disk

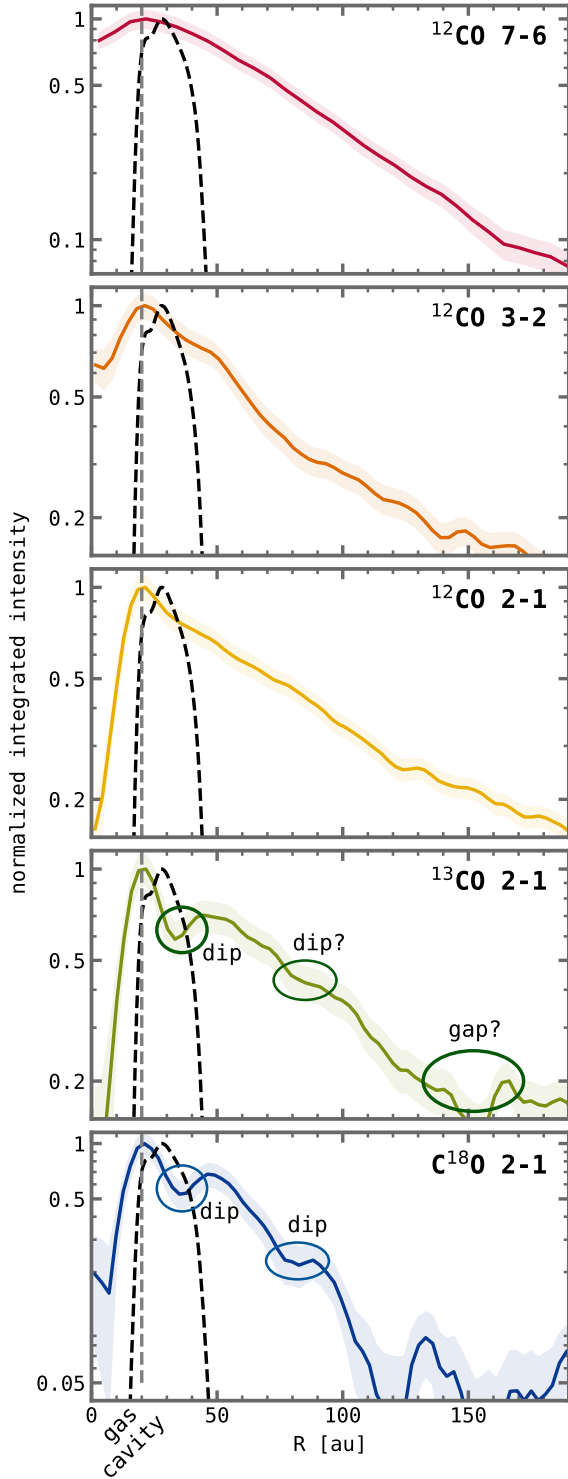


Fig. 4. Azimuthally averaged and normalized radial integrated intensity profiles for the different CO lines. A radial profile of the Band 6 mm continuum is included as black dashed lines. The gray vertical dashed line marks the location inside which the gas emission rapidly drops (gas cavity). Some features of the profiles are annotated.

geometry as obtained from the models presented in Sect. 3 and Table 4. The gas intensity significantly drops inside of ~ 20 au for all lines, thus just inside the dust cavity. We note the location of the drop as the gas cavity, but this represents an upper limit. To get a better estimate of the actual gas cavity, a more thorough analysis of the temperature structure across the cavity such

Table 3. Parameterization adopted for the DISCMINER models in this work^(a).

Attribute	Parameterization
Orientation	i, PA, x_c, y_c
Rotation velocity	$v_K = \sqrt{GM_*/r^3} \cdot R, v_{\text{sys}}$
Emission surface	$z_{u,l} = z_{u0,l0}(R/D_0)^p \cdot \exp[-(R/R_t)^q]$
Peak intensity	$I_p = I_0(R/D_0)^{p0}(z/D_0)^q, R < R_{\text{break}}$ $I_p = I_0(R/D_0)^{p1}(z/D_0)^q, R > R_{\text{break}}$ $I_p = 0, R > R_{\text{out}}$
Line width	$L_w = L_{w0}(R/D_0)^p(z/D_0)^q$
Line slope	$L_s = L_{s0}(R/D_0)^p$

Notes. ^(a) D_0 represents a normalization constant, set to 100 au, R and z are the disk cylindrical coordinates, and r the spherical radius. G is the gravitational constant, all other variables are left as free parameters.

as in Leemker et al. (2022) or a kinematical approach such as in Bosman et al. (2021) is required. In addition to the inner cavity, a prominent drop of emission is seen in ^{13}CO and C^{18}O at ~ 35 au. This intensity drop coincides with the continuum emission and thus may be caused by continuum absorption, rather than representing a gas gap. Another intensity drop is observed in C^{18}O around 85 au (and potentially ^{13}CO) and in ^{13}CO around 150 au, the C^{18}O emission is too noisy around this location. This dip corresponds to the gap tentatively detected in the channel maps. Continuum absorption is unlikely responsible for this substructure as it peaks around 200 au, but (particularly for C^{18}O) higher sensitivity data are needed to quantify a gas gap at these radii.

3. Analysis

3.1. Model setup

We used the DISCMINER code introduced in Izquierdo et al. (2021) to model the intensity channels (see Fig. 2) of the HD 100546 disk. In the following, we outline the basic modeling approach but refer the reader to Izquierdo et al. (2021) for the full details of the package. In the DISCMINER, parametric prescriptions are adopted to reproduce the intensity channel maps from molecular emission. The parameters used in this work are briefly summarized as follows (see Table 3).

To describe the orientation of the disk, we used the position angle (PA), inclination (i), and disk center (x_c, y_c). For the rotation velocity, we adopted a Keplerian rotation, using the stellar mass (M_*), and source systemic velocity (v_{sys}), to describe the background velocity. The upper and lower emission surfaces are controlled by the height (z) above and below the disk midplane. Here, we used a power law with an exponential tapering. The line peak intensity, line width, and line slope across the disk radial and vertical extent are parameterized with simple power laws of the disk cylindrical coordinates (R, z). For the peak intensity, we selected a combination of two power laws, describing the intensity profile inside and outside a radius R_{break} , respectively. By doing so, we were able to account for a decrease in intensity inside the gas cavity. For radii larger than the parameter, R_{out} , the peak intensity was set to zero.

Subsequently, the DISCMINER is coupled with the Markov chain Monte Carlo (MCMC) random sampler EMCEE (Foreman-Mackey et al. 2013) to find those model parameters that best recover the intensity of the observed data cube. The different physical and morphological properties of the disk are

thus modeled simultaneously to give a comprehensive view of the gas substructures and kinematics. From the disk attributes, a model for the line profiles and data channels is generated. The modeled intensity I_m is described by a generalized bell kernel

$$I_m(R, z, v_{\text{ch}}) = I_p \left(1 + \left| \frac{v_{\text{ch}} - v_{\text{K}, \text{los}}}{L_w} \right| 2L_s \right)^{-1}, \quad (1)$$

as a function of the disk cylindrical coordinates (R, z) and velocity channel (v_{ch}) , while I_p is the peak intensity, L_w is half the line width at half power, L_s is the line slope, and $v_{\text{K}, \text{los}}$ is the Keplerian line-of-sight velocity. The vertical coordinate z is determined by the height of both the upper and the lower disk surface; thus, each property except for L_s has two descriptions. The contribution of the upper and lower emitting surfaces are merged into a single-line profile by selecting the highest intensity between bell profiles computed for both surfaces independently in each velocity channel and pixel.

To initialize the EMCEE sampler, we chose the inclination, position angle, and stellar mass found by the models of Wölfer et al. (2023) and guessed the other parameters using the interactive prototyping tool of the DISCMINER, which allowed us to compare the morphology of the model and data channel maps as well as line profiles by eye. The MCMC was then run with a varying number of walkers (depending on the number of fitting parameters) until convergence and the posterior distribution was sampled from the last 1000 steps. The noise of the data was taken into account in the fit: at each data pixel, the standard deviation of the residual intensities in line-free channels was calculated and adapted as a weighting factor for the likelihood function to be maximized by the sampler (see Izquierdo et al. 2021). To ensure that the noise of the individual pixels was approximately independent of their neighboring pixels, we down-sampled the data with at least one beam while still ensuring that we had enough pixels left for the fit (>50).

The HD 100546 disk has previously been proposed to be warped in the center (Walsh et al. 2017). This could result in a temperature difference, potentially producing an elevation asymmetry, as it has been observed in CO emission of the Elias 2-27 disk (Paneque-Carreño et al. 2021). Moreover, the system is still surrounded by a diffuse envelope (Grady et al. 2001) and the infall of material from that envelope onto the disk could also result in such an asymmetry. To check for asymmetries between the blue- and redshifted sides of the disk, we conducted additional runs where only half of the channels of the according side were modeled instead of using the full cube. In these runs, we fixed the disk orientation (i.e., the inclination and position angle) to those of the full cube ^{12}CO model to ensure that any potential asymmetries are independent of the disk's orientation. In a similar way, for C^{18}O , we fixed the disk orientation (see Izquierdo et al. 2025) and switched off the lower surface in all runs since the channels appear to be very flat. Even though this is true also for ^{13}CO , we ran models that fit for both surfaces and models where the lower surface was not included, yielding similar results. In the following analysis, we used the models where both surfaces were modeled. In the case of ^{12}CO 7–6, only the models that accounted for the blue- and redshifted side separately converged, when the lower surface was included in the fit. To model the full cube, we therefore conducted additional runs with the lower surface switched off, which converged well and are thus used in our following results.

3.2. Fitting results

The best-fit parameters are summarized in Table 4 for the models fitting the full cube and in Tables C.1 and C.2 for the models fitting the blue- and redshifted side separately. The retrieved orientation of the disk is very similar in all models, resulting in a mean inclination, i , and position angle, PA, of $42.76 \pm 2.39^\circ$ and $322.52 \pm 1.67^\circ$, respectively. We note that the convention used for the position angle is that it is measured from the north to the red-shifted side of the disk. A slightly larger, but still small scatter is found for the stellar mass ($2.1 \pm 0.13 M_\odot$), which is relatively sensitive to changes in the model. For the Band 6 and Band 7 data, the systemic velocity is very close to the expected value of 5.7 km s^{-1} ; however, for the ^{12}CO 7–6, it is fitted as 5.4 km s^{-1} . As mentioned before, this offset from the source velocity found in the literature (e.g., Walsh et al. 2014, 2017) can be seen in the channel and rotation maps. The trend of decreasing line width from ^{12}CO 7–6 to C^{18}O is picked up by the DISCMINER. The radius, R_{break} , where a switch in the peak intensity profiles is happening, generally increases toward C^{18}O (exception is ^{12}CO 3–2). This can be explained by the inner gas cavity ($<20 \text{ au}$) becoming more pronounced in the more optically thin lines. We note however, that R_{break} marks the point where the intensity is maximal and not the actual cavity radius and other effects (such as temperature) influence its location.

3.2.1. Channel maps

In Fig. 5, we present a comparison of the data and best-fit model channels of ^{12}CO 2–1 alongside the residuals obtained from subtracting the model from the data. The channels are shown in steps of four around the central channel. The according plots of the other lines are included in Appendix D. The overall morphology of the data channels is well reproduced by the models, except for ^{12}CO 7–6, where the lower surface could not be modeled properly. The emission surfaces obtained from the models are overlaid as gray contours in the individual panels. For all lines, their morphology matches that of a rather flat and not very flared disk: the back side of the disk is barely visible and the azimuthal contours do not show any clear bending. While this is not unusual for ^{13}CO and C^{18}O , it is puzzling that we do not see a stronger manifestation of the vertical structure in ^{12}CO .

The surface of the disk is expected to become most visible in ^{12}CO 7–6. In Fig. D.2, we plot the channels as a combination of the models fitting only half of the cube. While the emission surface on the blueshifted side is still showing a flat morphology, the redshifted side appears much more elevated and flared. A similar exercise for the other ^{12}CO lines did not yield a significantly different emission surface compared to the one retrieved from the full cube. Another interesting point about the combined ^{12}CO 7–6 plot is that it shows that the vertical structure itself can produce apparent wiggles in the channels, which are nicely retrieved by the model, especially for the blueshifted side.

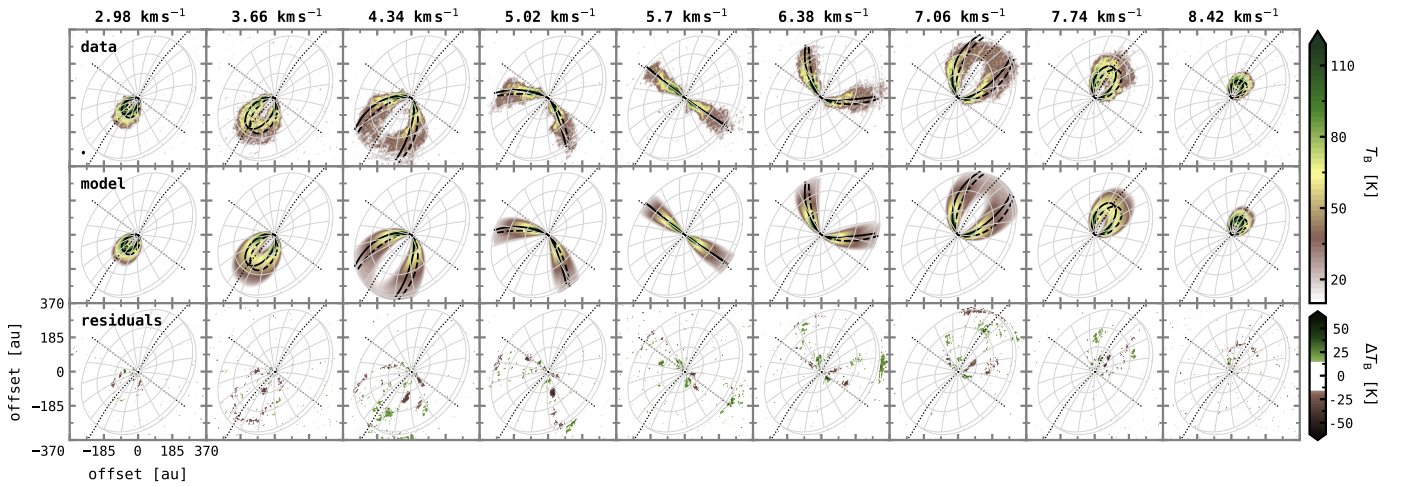
The residuals of the different lines partly reach high values, suggesting that a smooth Keplerian model cannot fully reproduce the data. These deviations from Keplerian rotation can be used to unveil the mechanisms being at play, including massive planets but also other physical processes such as disk winds, hydrodynamical instabilities, or turbulence.

3.2.2. Observables

From the line intensity profiles modeled by the DISCMINER, we extracted three observables to search for substructures in the gas

Table 4. Best-fit results of the modeling of the full cubes with the DISCMINER.

Attribute	Parameter	Unit	^{12}CO 7–6	^{12}CO 3–2	^{12}CO 2–1	^{13}CO 2–1	C^{18}O 2–1
Orientation	i	$^\circ$	39.30	44.29	44.40	43.03	fixed
	PA	$^\circ$	320.96	323.30vi run	323.37	324.45	fixed
	x_c	au	−0.44	4.86	1.45	0.36	3.87
	y_c	au	−2.20	−7.06	−1.38	−1.04	−3.83
Velocity	M_*	$M_\odot$	2.21	1.93	2.01	2.16	2.23
	v_{sys}	km s^{-1}	5.38	5.65	5.65	5.64	5.65
Upper surface	z_0	au	19.32	23.11	19.99	2.59	9.51
	p	–	0.85	0.86	0.82	0.02	0.17
	q	–	1.88	2.59	3.68	4.99	1.91
	R_t	au	292.86	306.15	329.45	212.03	199.67
Lower surface	z_0	au	–	13.37	25.98	43.08	–
	p	–	–	1.05	1.74	0.98	–
	q	–	–	1.07	0.98	2.48	–
	R_t	au	–	341.71	142.61	21.25	–
Intensity	I_0	Jy px^{-1}	7.04	0.63	0.24	0.06	0.01
	p_0	–	−0.97	0.59	−0.18	0.92	1.06
	p_1	–	−1.40	−0.82	−1.04	−0.43	−2.23
	q	–	0.83	0.40	0.61	0.30	0.004
	R_{break}	au	54.98	42.87	55.15	58.62	61.24
	R_{out}	au	322.04	393.46	375.36	326.57	247.54
Line width	L_W	km s^{-1}	2.01	0.70	0.68	0.28	0.02
	p	–	−0.90	−0.49	−0.56	−0.82	−1.05
	q	–	0.44	−0.05	0.03	−0.10	−1.00
Line slope	L_S	–	2.03	1.94	2.12	1.75	2.33
	p	–	0.29	0.27	0.37	0.05	0.34


Fig. 5. Examples of the intensity channels of ^{12}CO 2–1 (top), shown in steps of four around the central channel, alongside the best-fit model obtained with the DISCMINER (middle) and the corresponding residuals (bottom). The iso-velocity curves of the upper and lower surfaces are overlaid as solid and dashed lines, respectively. The emitting surface and disk axes are plotted in the background as gray contours and dotted lines, respectively. The beam of the observation is indicated in the bottom left corner of the first panel.

disk of HD 100546: the line width, centroid velocity, and peak intensity or brightness temperature. These are computed from Gaussian kernels, which are fitted to both the data and the model and illustrated in Fig. 6 (left and middle panels) for the ^{12}CO 2–1 line. The residuals resulting from the deviations of the data from the model are depicted in the right panels. The different observables can be used to trace various physical properties of

the disk. The line width and peak intensity are shaped by both the gas temperature and density, the line width can additionally be used to trace turbulent motions. The gas motions that are manifested in the kinematics are driven by dynamical (and often coupled) processes, including the gravitational influence of embedded (massive) bodies. Using the vertical emission structure together with the orientation of the disk as modeled by the

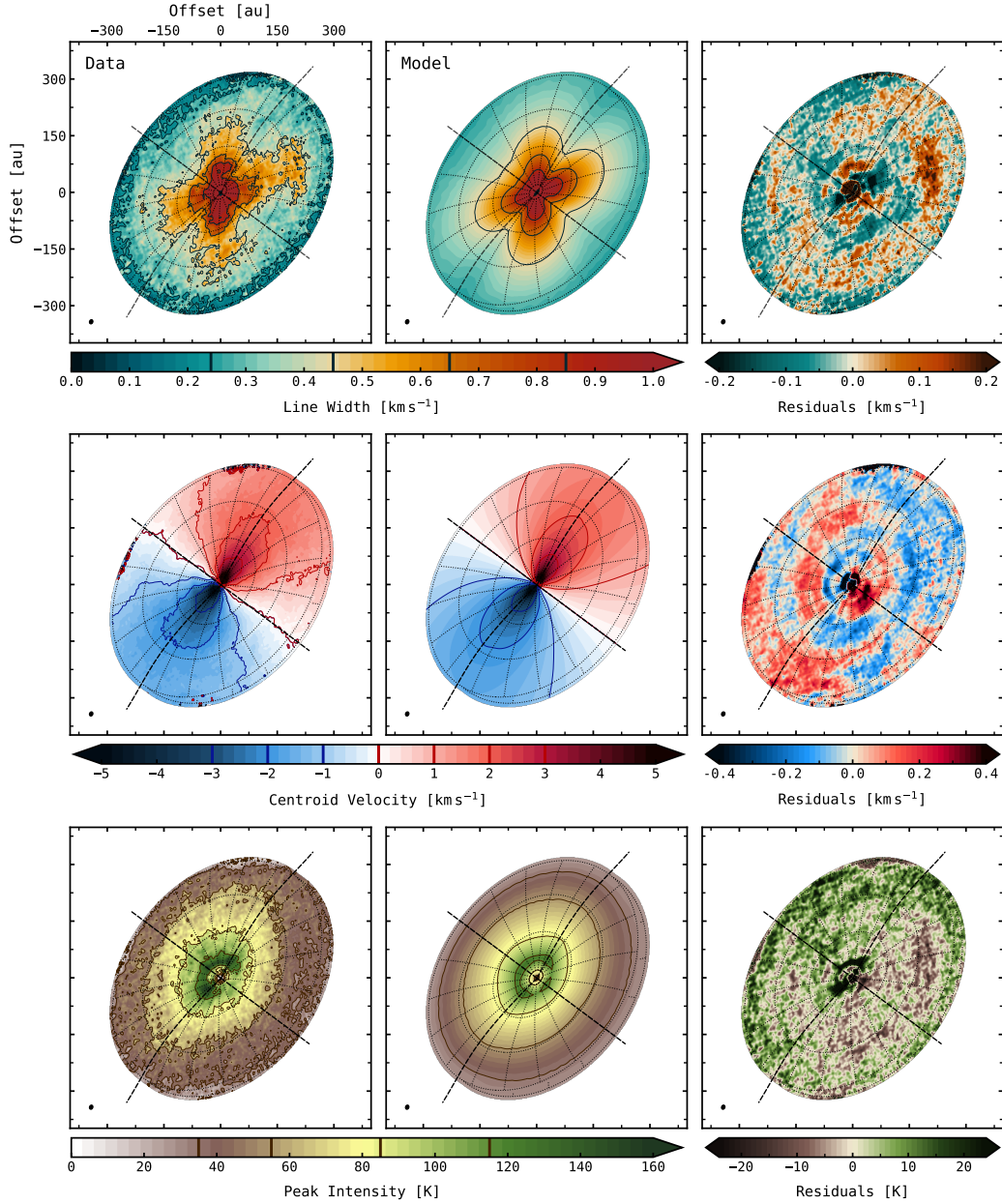


Fig. 6. Observables extracted from the modeled line intensity, shown for ^{12}CO 2–1 as an example. Displayed are the line widths (top), centroid velocities (middle), and peak intensities (bottom) for the data and best-fit model. The residuals, showing the differences between the data and model, are included in the last column. Some contour levels, indicated in the color bars, are included to ease comparison. The emission surface and disk axes are plotted as dotted and dashed lines, respectively.

DISCMINER, the observables can be deprojected onto the disk’s reference frame and their substructures can be analyzed in terms of location, magnitude, and extent.

4. Results

4.1. Kinematics

In Fig. 7, we show the centroid velocity residuals for all five lines, ordered from the brightest to the faintest, and deprojected onto the disk frame. It is striking, that prominent spiral features are visible in all maps: in ^{12}CO 7–6, a large coherent spiral runs from the inner disk around 50 au and 90° out to radii of 300 au, and possibly further, covering more than one full azimuth. In ^{12}CO 3–2, similar features can be discerned, yet they are not as connected. In ^{12}CO 2–1, which has a higher spatial resolution,

the spiral seems to consist of several arms which are slightly more tightly wound than in ^{12}CO 7–6. In ^{13}CO and C^{18}O , the spirals become even more tightly wound. The anchoring point of the spiral substructures lies between 50 and 150 au and between 60 and 120° .

To further analyze the spiral features, we compute the binned residuals as radius versus azimuth, presented in Fig. 8. For each azimuthal bin every 10° , we then fit a Gaussian to the peaks in the spirals region along the radial direction. The resulting points are overlaid in Fig. 8. Lastly, we fit an Archimedean or linear spiral,

$$r = a + b\phi, \quad (2)$$

and a logarithmic spiral,

$$r = ae^{b\phi}, \quad (3)$$

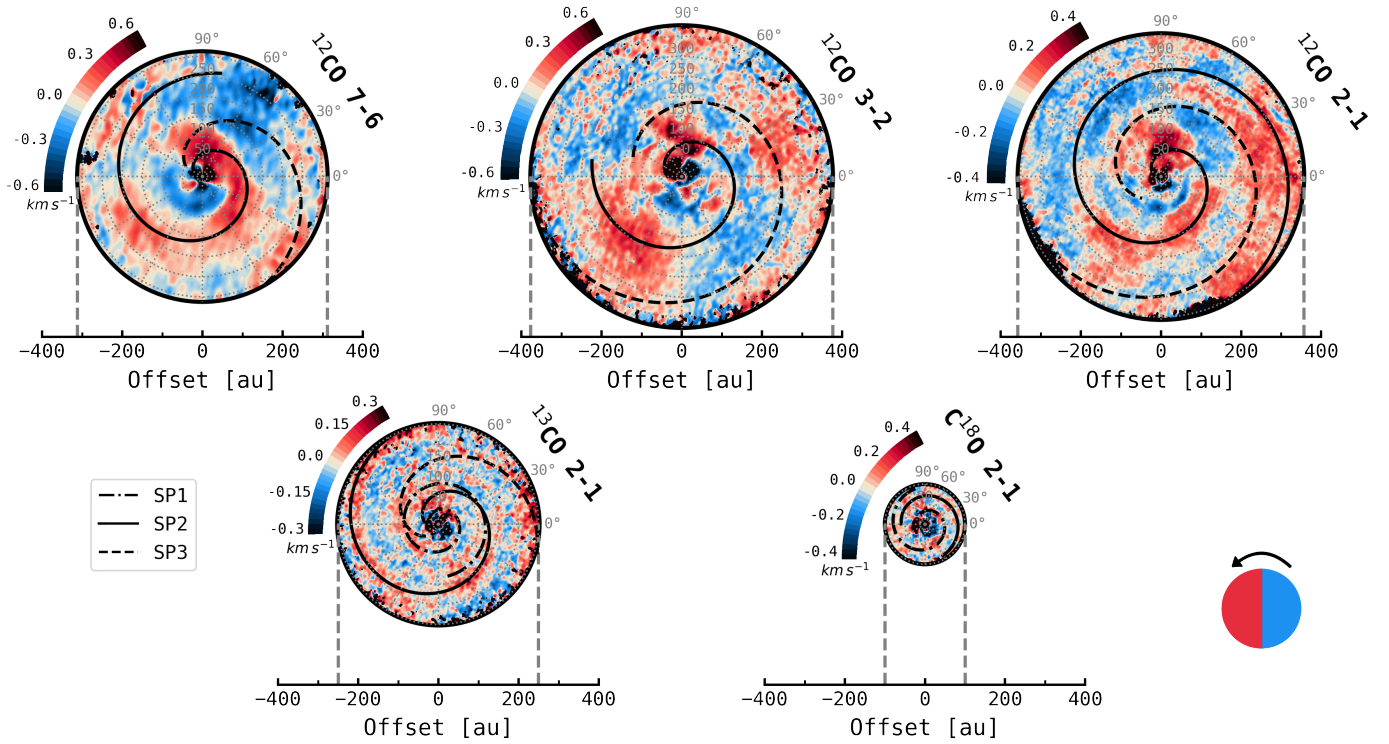


Fig. 7. Centroid velocity residuals, shown for the five lines studied in this work. All lines exhibit extended spiral substructures. A linear parameterization of the spirals is overlaid as black lines. The spirals are labeled depending on their (increasing) radius as SP1, SP2, and SP3. The circle in the lower right corner indicates the blue- and redshifted sides of the disk.

Table 5. Parameters to reproduce the spirals with linear and logarithmic functions.

	Parameter	$^{12}\text{CO 7-6}$	$^{12}\text{CO 3-2}$	$^{12}\text{CO 2-1}$	$^{13}\text{CO 2-1}$	$\text{C}^{18}\text{O 2-1}$	$^{12}\text{CO 2-1 } T_{\text{B}}$
Linear	SP1 a (au)	–	–	–	52.45	48.29	96.19
	SP1 b ($^{\circ} \text{ au}^{-1}$)	–	–	–	–0.18	–0.17	–0.17
	SP2 a	107.47	128.18	110.93	124.01	82.28	88.17
	SP2 b	–0.55	–0.52	–0.57	–0.52	–0.13	–1.05
	SP3 a	235.79	246.14	234.18	242.24	–	261.10
	SP3 b	–1.26	–0.73	–0.71	–0.89	–	–0.35
Logarithmic	SP1 a (au)	–	–	–	49.95	45.90	–
	SP1 b ($^{\circ} \text{ au}^{-1}$)	–	–	–	–0.0033	–0.0035	–
	SP2 a	96.13	114.95	102.39	116.02	81.89	–
	SP2 b	–0.0051	–0.0044	–0.0047	–0.0039	–0.0016	–
	SP3 a	227.42	238.05	226.14	244.09	–	–
	SP3 b	–0.0056	–0.0027	–0.0028	–0.0050	–	–

where r is the radius and ϕ the polar angle of the spiral, to the retrieved points. In Fig. 7, we overlay the obtained linear spirals, the logarithmic spirals are presented in Fig. E.1. The overall morphology of the spiral substructures is well represented by both parameterizations, however, the logarithmic spirals tend to deviate more from the features in the outer disk, while they better reproduce the bending in the inner disk than the linear spiral, which can by definition not account for that. The different spirals are labeled as SP1, SP2, and SP3 depending on their approximate radial locations (i.e., SP1 is the spiral closest in, SP3 the farthest), yet there is an offset between some of the spirals (namely SP2 in C^{18}O and the other lines) and it is difficult to say for sure if they are tracing the same structure. Also, some of the spirals are not visible as a connected structure. Comparing the three ^{12}CO lines, it seems that a blue feature, separating the inner and

outer parts of the spiral, is emerging more and more from $^{12}\text{CO 2-1}$ to $^{12}\text{CO 7-6}$. This suggests that other mechanisms shaping the kinematics may be coming into play, for example, interactions with the disk’s environment (such as infall) that are adding a large velocity dispersion.

The parameters of the individual spiral prescriptions are presented in Table 5. They can be used to compute the opening angle or pitch angle β of the spirals with

$$\tan \beta = \left| \frac{dr}{d\phi} \right| \cdot \frac{1}{r}. \quad (4)$$

This results in a constant pitch angle for the logarithmic and a radially varying one for the linear spirals. The pitch angles are

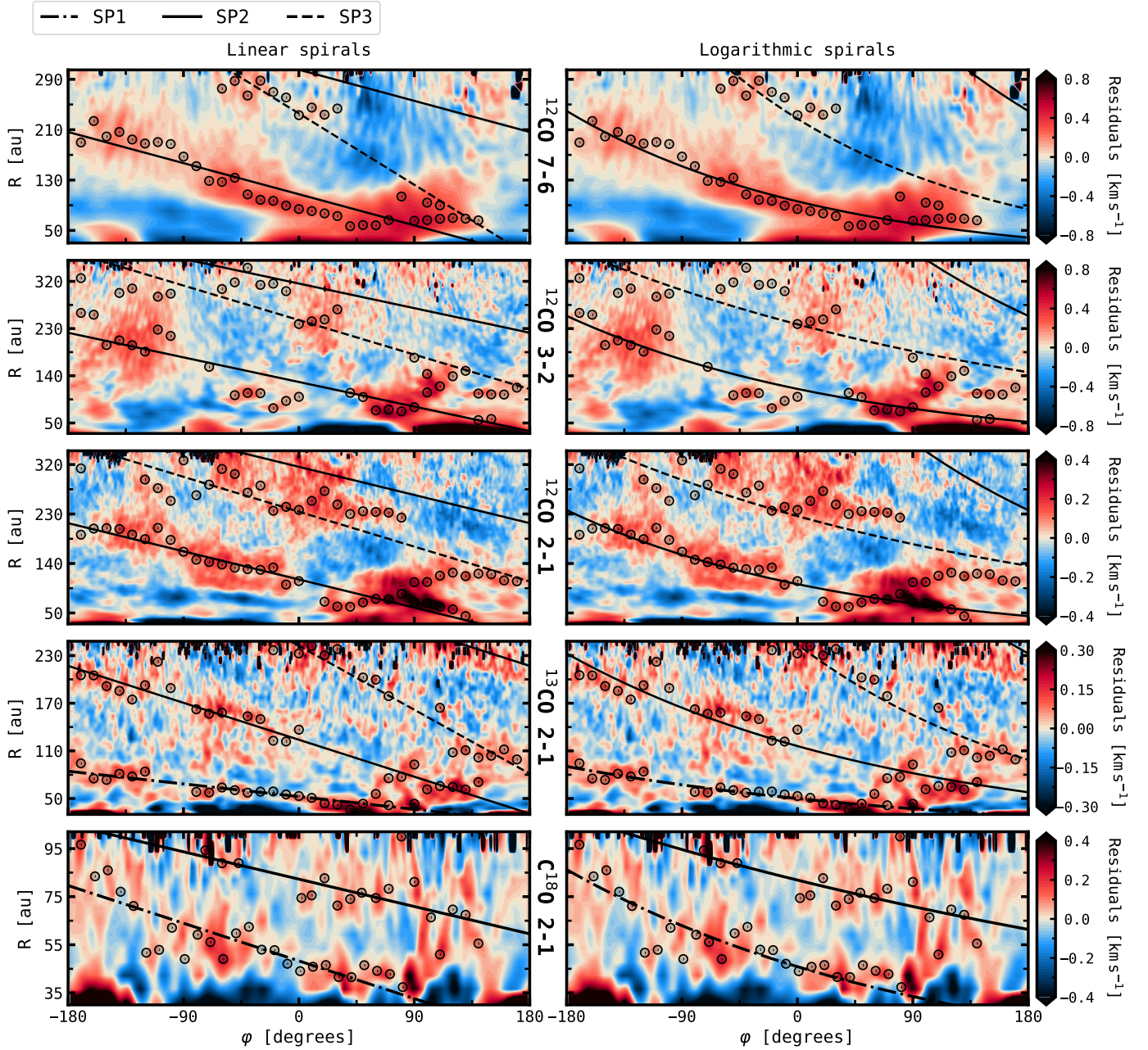


Fig. 8. Azimuthal deprojection of the centroid velocity residuals of the five lines, shown with overlaid linear (left) and logarithmic (right) fits of the values (circles) returned by a Gaussian fit of the peaks in the spiral region. The spirals are labeled depending on their (increasing) radius as SP1, SP2, and SP3.

plotted in Fig. 9. For the linear spirals, the pitch angles are relatively small in the outer disk regions but rapidly increase inside of ~ 50 au. The constant pitch angles found from the logarithmic spirals have values below 20° . For SP1, the pitch angles are in good agreement for both ^{13}CO and C^{18}O . Similarly, the linear pitch angles of SP2 align for all lines except C^{18}O , where we are likely tracing a different substructure. Moreover, the data quality may not be sufficient to properly analyze the spiral patterns in C^{18}O . The logarithmic pitch angle of SP2 in ^{13}CO is below that of the ^{12}CO lines. Related to that, there appears to be a trend of decreasing pitch angle with height for SP2 and SP3. This may be in agreement with the predictions of Juhász & Rosotti (2018) from modeling of thermal stratification, however, to properly test this scenario, the spirals would need to be traced a higher

resolution and sensitivity. We further note, that the pitch angles overall decrease from SP3 to SP1.

4.2. Peak intensities and line widths

The residuals of the peak intensity and line widths are displayed in the Appendix in Figs. F.1 and F.2, again shown ordered from the brightest to the faintest line. The substructures in the peak intensity and line width are less clear than in the kinematics and no coherent spiral structures can be discerned. In ^{12}CO 7–6, the upper half of the disk (corresponding to the southwest side of the disk in disk coordinates) happens to be colder while the lower half is hotter. This corresponds to the brightness asymmetry mentioned before, which is seen in the channels. The

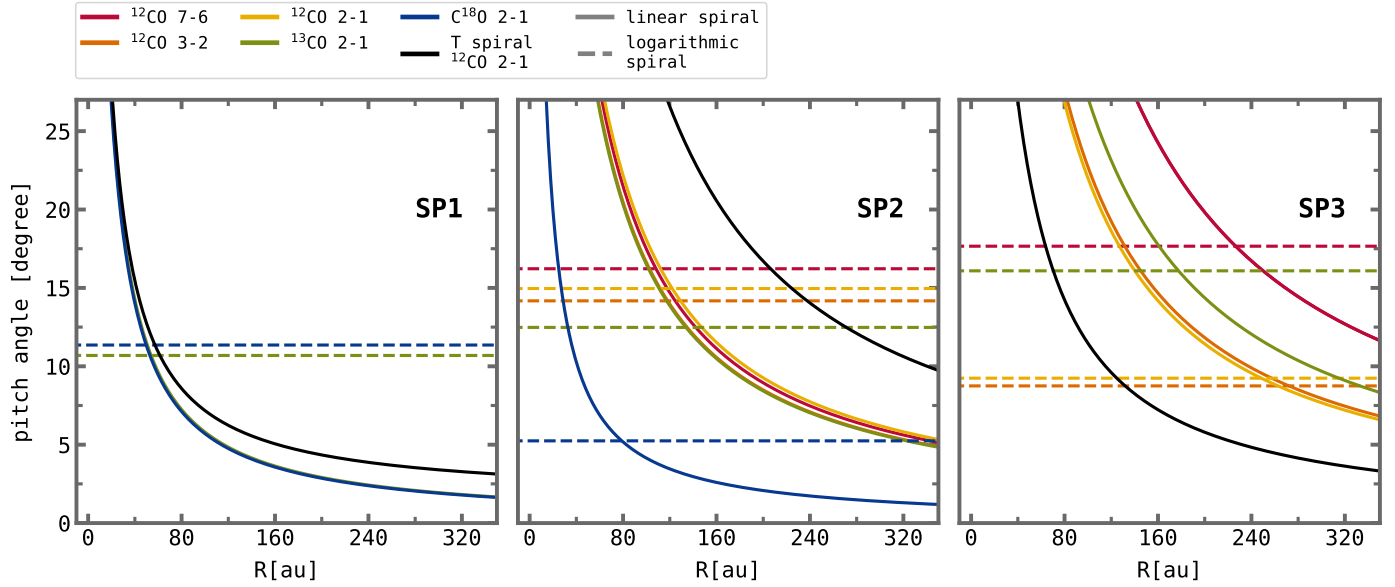


Fig. 9. Pitch angles of the spirals observed in the kinematics (and peak intensity of ^{12}CO 2–1), obtained from a linear and a logarithmic fit.

line widths on the other hand are increased in the upper half of the disk, but they are decreased in the lower side. Together, this may suggest that the surface density is larger on the upper (south) side, thus broadening the line width and at the same time lowering the temperature. The additional material could be a result of infall processes, which do not only increase the density but also add a large velocity dispersion, which affects the shape of the line profile. In ^{12}CO 3–2, a similar pattern opposite pattern (i.e., enhanced temperatures correspond to decreased line widths) is seen in the south side of the disk. Another feature is a localized temperature enhancement around 150 au and 60° , which corresponds to the spot already seen in the channel maps. The features in ^{12}CO 3–2 are very difficult to interpret and higher resolution data (including the short and long baseline observations with the same setup) are needed to make any quantitative remarks. Similarly, higher sensitivity data are needed for ^{13}CO and C^{18}O , which show cross-like patterns in the line width residuals, resulting from the missing fit of the lower surface.

Somewhat clearer substructures can be discerned in ^{12}CO 2–1, for which we show the projected and polar-deprojected maps in Fig. 10. In the peak intensity, three tentative spiral- or arc-like structures are visible, which we reproduce with the same methods as described above and with a linear function. The parameters and pitch angles obtained for these spirals are included in Table 5 and Fig. 9. Furthermore, a prominent ring of enhanced line widths can be distinguished between ≈ 125 – 330 au, showing a particularly bright region between 100 – 150° . The ring co-locates with both low and high temperatures and it is thus difficult to say if the lines are broadened by temperature effects or density enhancements. The localized region on the other hand coincides with a low-temperature spot and may be tracing a region of dense gas material or turbulent motions rather than temperature. The patterns seen in the peak intensity residuals of ^{12}CO 7–6 and ^{12}CO 3–2 somewhat resemble those seen in ^{12}CO 2–1 in the south regions of the disk. Similarly the line width patterns of ^{12}CO 3–2 and ^{12}CO 2–1 are somewhat consistent. It is possible that resolution and sensitivity effects are washing out the features in the B7 and B10 emission and that the spiral patterns seen in the peak intensity of ^{12}CO 2–1 are not separated, but blended together instead.

4.3. Emission heights

In Fig. 11, we present the emission layers of the upper and, in case of ^{12}CO , lower surfaces of the disk, extracted from the DISCMINER models. Here we plot the profiles obtained from runs fitting for the full cube (yellow) as well as the blue- and redshifted sides only. The curves show that while the optically thick ^{12}CO emission is coming from more elevated disk layers, particularly in the higher transitions, ^{13}CO and ^{18}CO originate from similar layers that are very close to the midplane. Furthermore, an asymmetry between the red- and blueshifted side is revealed (see also Figure G.3), which becomes particularly strong for ^{12}CO 7–6: the emission of the redshifted side of the disk is coming from higher disk layers (~ 25 au difference for ^{12}CO 7–6) than that of the blueshifted side, which can already be seen in the channel maps (see for example Figure D.2). Such an asymmetry has been detected before only for the Elias 2–27 disk, a massive and gravitationally unstable disk, that may be affected by infall or an inner warp (Paneque-Carreño et al. 2021, 2022). While the asymmetry between the red- and blue-shifted sides is consistently traced by the emission lines, the magnitude of the difference may vary depending on the modeling procedure. Especially for the higher J lines, the channels are twisted, which may have affected the fit of the emission surface.

4.4. Azimuthal averages

In Fig. 12, we plot the azimuthally averaged residuals, including all three velocity perturbations v_ϕ , v_z , v_r , aside from the line width and peak intensity deviations. The derivation of the individual velocity components is detailed in Izquierdo et al. (2023, 2025). In Fig. 12, we mark the locations where planets have previously been proposed as well as the centers of the two observed dust rings (B28 and B200). We further annotate some trends seen in the profiles such as the sign of the velocity gradient in the azimuthal perturbations (tracing pressure minima and maxima), upwards and downwards flows in the vertical perturbations, negative and positive gradients in the radial velocity, and local minima or maxima in the line width and peak intensity. We discuss some of the trends seen in the averages in the following,

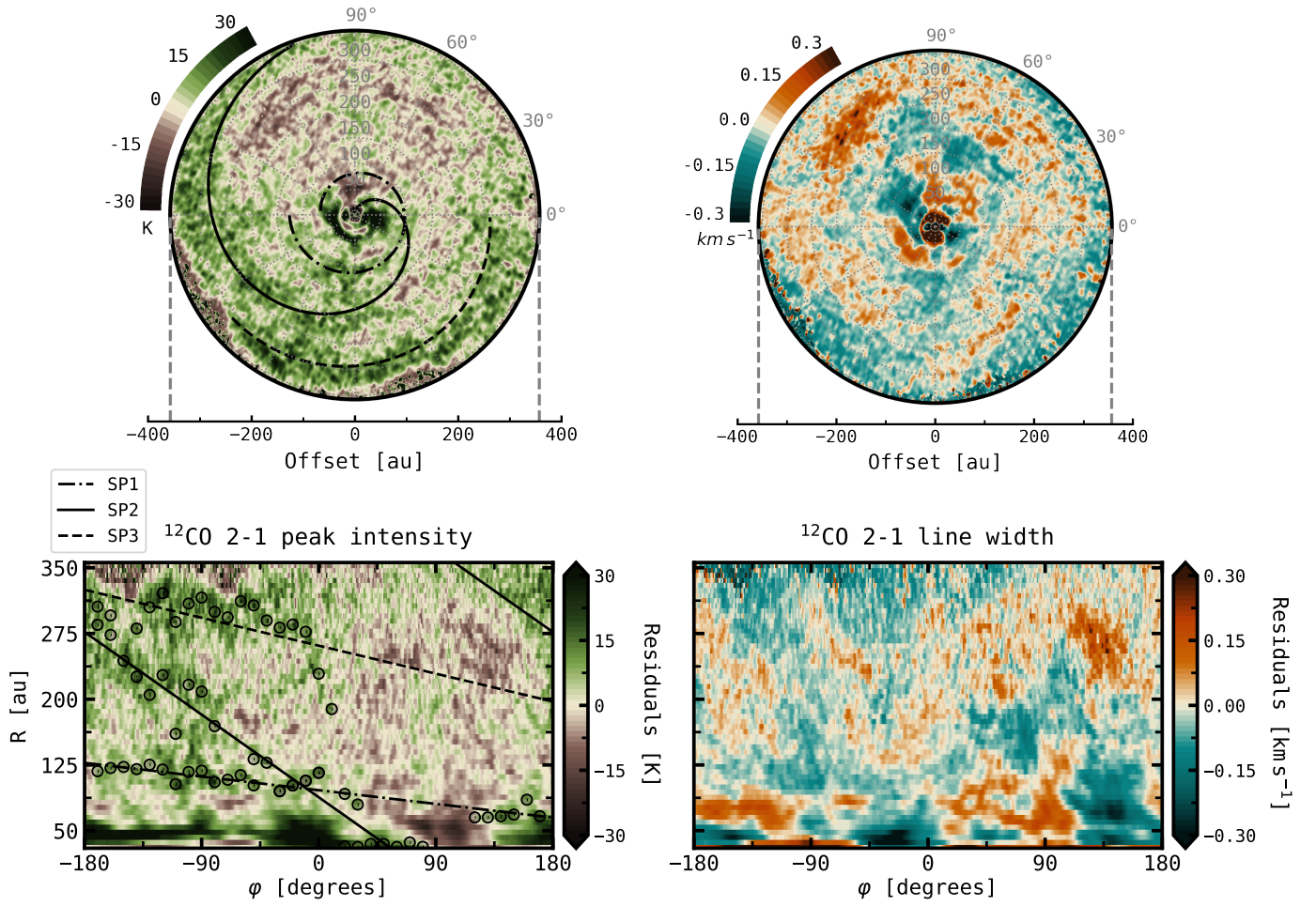


Fig. 10. Peak intensity (left) and line width (right) residuals of ^{12}CO 2-1. Shown are the deprojected maps (top) and an azimuthal deprojection (bottom). In the peak intensity, three parameterizations of a linear spiral are overlaid, obtained from a Gaussian fit of the peaks in the spirals region.

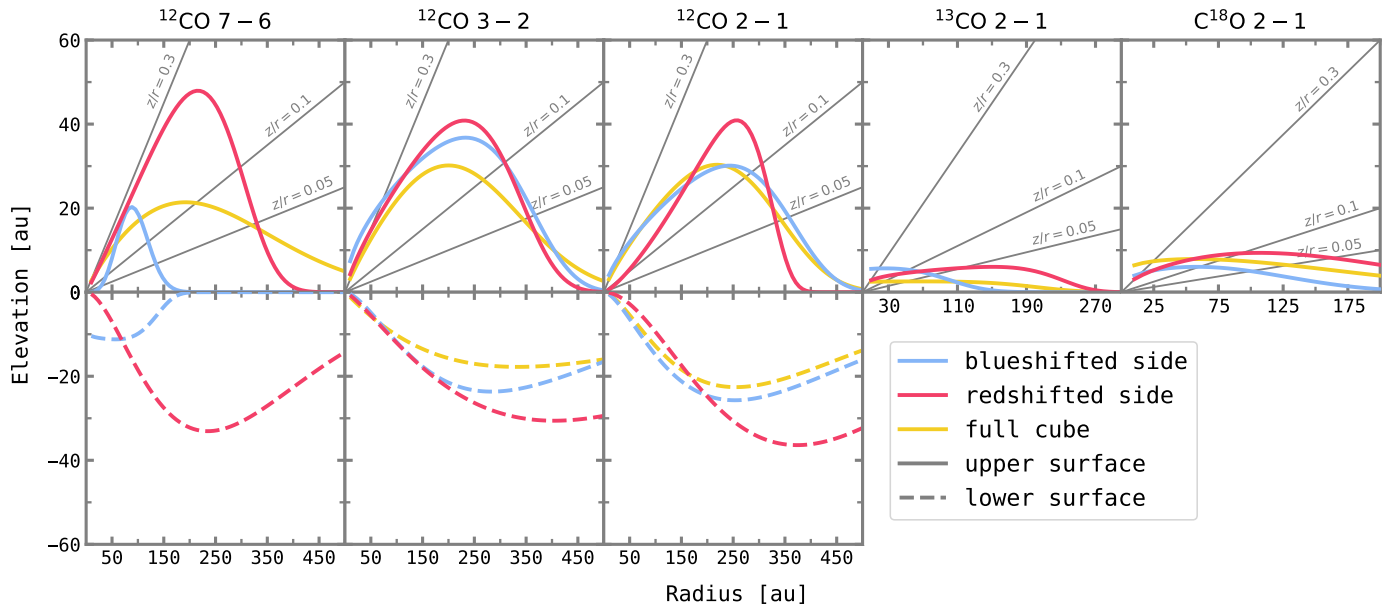


Fig. 11. Upper (top) and lower (bottom) emission surfaces of the five molecular lines, shown for the fits of the full cube and the fit of the blue- and redshifted sides only.

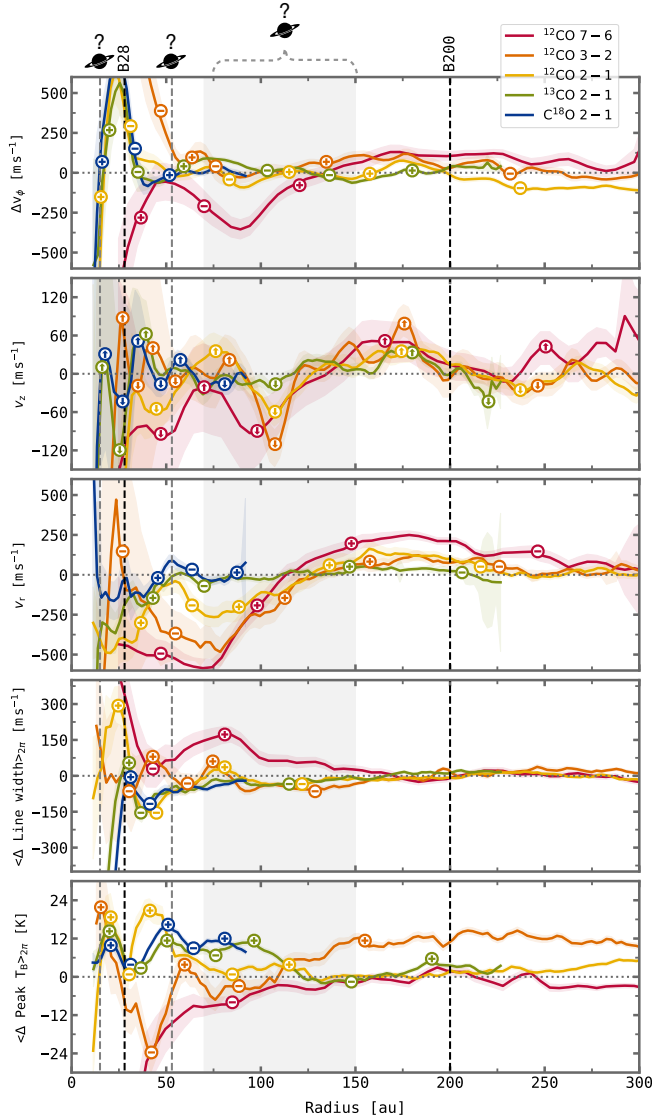


Fig. 12. Azimuthally averaged profiles of the three velocity components (top three panels), line width (fourth panel), and peak intensity (lower panel) residuals, shown for all five lines. The centers of the dust rings and locations of previously proposed planets are marked by dashed lines and the shaded region. In the top panel, the sign of the velocity gradient is indicated with plus and minus signs. In the second row, flows hinting at gas moving away from and toward the disk midplane are highlighted as up and down arrows. The gradients of outward and inward flows are marked by plus and minus signs in the third panel. Local line width and temperature maxima and minima are indicated with plus and minus signs in the fourth and fifth panel, respectively.

however, we note that their computation is based on the assumption of axisymmetry, which does not necessarily hold. In fact, the spiral structures seen in the kinematics suggest the perturbations to be non-symmetric. Nevertheless, the curves are still useful to get an indication of some general trends.

At the location of the dust rings, negative velocity gradients are seen in all lines except ^{12}CO 7–6, tracing pressure bumps which can account for the formation of the rings. In this context, the more optically thin lines tracing regions closer to the midplane can better constrain the underlying density profile than the optically thick lines which are affected by the temperature. Thus, it is not surprising that ^{12}CO 7–6 is showing an opposite trend. Inside the inner dust cavity, a strong positive gradient is

present and downward flows indicate the gas material falling into the cavity. However, close to the star, beam smearing and optical depth effects are becoming significant, resulting in large errors, and within ~ 25 au, the profiles have to be treated with caution. For the same reason, we were not able to draw any conclusions on the features seen around the innermost planet candidate at ~ 15 au. Around the location of the second planet candidate at ~ 53 au, both ^{13}CO and C^{18}O show positive gradients, supporting the presence of a gas gap that indeed may be carved by a massive companion. Again, an opposite trend is visible in ^{12}CO but as mentioned above, ^{13}CO and C^{18}O are more likely to trace pressure minima related to a low gas density. Just inside the planet candidate’s location, downward flows are seen in all lines, further supporting the presence of a companion. Moreover, there are line width minima that align well with those downward flows. Between 50 and 150 au, a change of the gradient of the radial velocity is observed in all lines, corresponding to inward motions inside of the ~ 100 au and outward motions outside of ~ 100 au. The brightness temperature shows strong fluctuations inside of ~ 100 au, which are hard to put into context with the other substructures and their origin cannot really be assessed.

Except for C^{18}O , for which the emission is not as extended, positive azimuthal velocity gradients and significant downward flows are present in all molecular tracers between 75–125 au, which coincides with the dust gap found by Fedele et al. (2021), the third proposed location of a planet candidate, the location of the bright spot in ^{12}CO 3–2, and the gap seen in the radial profile of ^{13}CO . For most of the radii, where the ring of enhanced line widths is observed in ^{12}CO 2–1 (see Figure 10), a negative azimuthal velocity gradient is found, supporting that we are indeed tracing a gas ring.

5. Discussion

5.1. On the planet candidate at 50 au

All molecular tracers analyzed in this study exhibit extended spiral structures in the kinematical residuals, which we reproduce with linear and logarithmic functions (Figs. 7 and 8). Their consistency suggests them to be real features tracing a common origin. The pitch angles of the linear spirals show small values at most radii but rapidly increase inside of ~ 50 au. Such a behavior is consistent with Lindblad-resonance-driven spiral wakes of a massive embedded companion (e.g., Ogilvie & Lubow 2002; Rafikov 2002; Bae & Zhu 2018a,b), which tend to increase only close to the location of the planet. The logarithmic spirals on the other hand show constant pitch angles below 20° , which are more consistent with tightly wound spirals excited by a planet through buoyancy resonances (Bae et al. 2021). In both cases, the spirals support the presence of a companion inside of ~ 50 au and therefore provide additional evidence for the planet candidate HD 100546 b, even though also the candidate HD 100546 c could, in principle, explain the formation of the spirals. Furthermore, the possibility of a binary rather than a planetary companion, as invoked by Norfolk et al. (2022), cannot be ruled out with the present data. The HD 100546 disk has previously been suggested to be warped in the center (Walsh et al. 2017), and a binary companion would provide a good explanation for both the extended spiral structures and the misaligned inner disk. Hydrodynamical simulations are needed to further distinguish between the Lindblad and buoyancy scenario and to make predictions on the companion mass and location.

While velocity spirals do not necessarily align with spiral features in the peak intensity, it is still puzzling that except for

^{12}CO 2–1, no counterpart of the kinematical spirals is found. Both in TW Hya (Teague et al. 2019b, 2022a,b) and CQ Tau (Wölfer et al. 2021), temperature spirals have been observed that overlap at least partly with the spirals in the velocity residuals, suggesting that there may be a physical mechanism behind their connection. In the companion scenario, the spiral density waves lead to an increase in surface density and thus to a higher CO opacity. The $\tau = 1$ layer is moved to a larger altitude, where the temperature is generally higher, resulting in the observed spiral substructure in the gas temperature (Phuong et al. 2020a,b). The lack of temperature features in HD 100546 is therefore unexpected, however, velocity spirals are more easily detected than those in the peak brightness temperature. The absence could therefore result from sensitivity effects and needs to be further investigated in the future.

Aside from dynamical interactions with a companion, spiral structures can also be a signpost of gravitational instability (GI; e.g., Rice et al. 2003). In that case, the pitch angles are expected to be comparable for the surface and the midplane layers, which are heated by shocks. On the other hand, the pitch angle is expected to increase toward the surface layers in the companion scenario if the disk is passively heated with a positive vertical temperature gradient (Juhász & Rosotti 2018). There is a tentative trend, that the spirals in HD 100546 become more tightly wound (lower pitch angle) toward the midplane, which would be supporting the predictions by Juhász & Rosotti (2018) and dynamical interactions rather than GI as the underlying mechanism. However, at the current data quality it is difficult to properly test this scenario. Higher resolution and sensitivity would be needed to better resolve the spirals and trace them radially further for ^{13}CO and C^{18}O .

5.2. On the planet candidate between 70–150 au

To explain the ringed substructures in the dust, a planet orbiting at large separations between 70–150 au has previously been proposed (Walsh et al. 2014; Pinilla et al. 2015; Fedele et al. 2021; Pyerin et al. 2021). In this region, we observe vertical motions directed down toward the midplane around ~ 110 au in ^{12}CO 3–2, ^{12}CO 2–1, and ^{13}CO 2–1, and around ~ 95 au in ^{12}CO 7–6 (Fig. 12, panel two). This shift is not surprising as the lines trace different heights in the disk which are governed by different physical and chemical processes. Such vertical flows are commonly associated with meridional flows around forming planets and similar motions have been observed before by Teague et al. (2019a), possibly tracing a depletion of gas material carved by an embedded companion. In that case, the gas is generally expected to radially flow toward the planet location, however, depending on the traced scale height, either inward or outward flows may be expected probing different parts of the meridional circulation. It appears that we are tracing the opposite behavior in v_r around the downward vertical motions, yet the expected trend is seen further in at smaller radii. Moreover, while the vertical motions are expected to behave coherently across different scale heights as we see here, this is different for radial motions, which makes it difficult to put the v_r pattern into context with a meridional flow (Teague et al. 2019a). Additionally, our estimates of the radial velocity flow may be biased by the complex spiral patterns in the disk.

The presence of a gas gap around 90–150 au is further supported by the positive sign of the azimuthal velocity gradient at these radii (Fig. 12), and tentative dips of emission in the azimuthally averaged radial intensity profiles of ^{13}CO (~ 150 au) and C^{18}O (~ 85 au) (Fig. 4). Lastly, a bright, localized spot stands

out in the velocity channels and peak intensity map of ^{12}CO 3–2 around 125 and 150 au, respectively. Altogether, these features strongly support the presence of a massive planet in the outer disk. However, higher sensitivity data at high resolutions are needed to confirm the robustness of the substructures. Moreover, a comparison with hydrodynamical models is crucial to understand if they can indeed be explained by a massive embedded body.

5.3. Origin of the asymmetry in emission heights

The CO emission of HD 100546 is marked by an asymmetry between the blue- and redshifted halves of the disk, which is especially pronounced in ^{12}CO 7–6 (Figs. 11 and G.3). Such an asymmetry has previously been detected only for the Elias 2–27 disk (Paneque-Carreño et al. 2021, 2022). One explanation could be given by infall onto the redshifted side of the disk. Infalling material results in an increase of the surface density, and thus the emission becomes optically thick in higher disk layers. Moreover, the temperature is altered as shocks will heat the layers on which the material is accreted (Hennebelle et al. 2017). Observations of scattered light have indeed revealed that the disk is surrounded by a diffuse envelope (Grady et al. 2001; Ardila et al. 2007). Another scenario that may account for the asymmetry is the presence of a warped inner disk casting a shadow over part of the outer disk, shielding it from stellar radiation and thus resulting in an azimuthal variation of the temperature, which has an immediate effect on the vertical structure of the disk. However, in the disk surface, which has a low surface density, the temperature decrements caused by a misaligned disk are expected to be smoothed out by thermal disk radiation (Casassus et al. 2019). Evidence for a misaligned inner disk is presented in Walsh et al. (2017), and the analysis by Bohn et al. (2022), who compare the position angle and inclination of the inner and the outer disk, places HD 100546 among the less aligned objects, yet, the scattered light images do not show signs of significant shadowing from a misaligned disk (Garufi et al. 2016). A warped inner disk can in principle be triggered by binary interactions or a misaligned planet (e.g., Nealon et al. 2018) but also the infall of material may produce such a structure (Bate et al. 2010; Sakai et al. 2019). We note, again, that even though the asymmetry is consistent across the emission lines, the magnitude of the difference may be enhanced due to the modeling procedure. Connected to that, it is surprising that there appears to be no strong asymmetry between the two sides in the scattered light images. The asymmetry should therefore be further investigated with higher sensitivity data.

6. Summary

In this work, we modeled the molecular line emission of five CO lines observed with ALMA in the circumstellar disk around HD 100546. Our main results are summarized as follows:

- Extended spiral features are resolved in the kinematics of all five lines. The peak intensity also shows indications of spirals, but only in ^{12}CO 2–1, likely due to limited sensitivity for the other lines. A ring and bright region of enhanced line widths are seen in the line width residuals of ^{12}CO 2–1;
- The spirals are well reproduced by a linear and/or a logarithmic function and exhibit small pitch angles that are consistent with Lindblad or Buoyancy spirals driven by a companion;

- A rapid increase of the pitch angles inside of ~ 50 au suggests an upper limit for the companion location around this radius, which is consistent with the planet candidate HD 100546 b or HD 100546 c. However, it might point to a binary companion, rather than a planet, as suggested by [Norfolk et al. \(2022\)](#);
- Several indications for a companion at larger separations (90–150 au) are present: downward flows toward the mid-plane and pressure minima around this region suggest a gas-depleted ring that may be carved by an unseen planet. In the radial curves of the integrated intensity of ^{13}CO 2–1 and C^{18}O 2–1, tentative gas gaps are visible at 150 and 85 au, respectively, which need to be confirmed with higher sensitivity data. Altogether, these features coincide with the dust gap observed by [Fedele et al. \(2021\)](#);
- The emission from the redshifted side appears more elevated compared to the blueshifted side of the disk. Such an asymmetry could result from infalling material on one side of the disk, which would increase the density and lift the optically thick emission layer. An alternative explanation could be temperature effects that result from a warped inner disk casting a shadow over the disk.

High-sensitivity, multiline, and multi-isotopologue data (of different molecules) taken at high spectral and spatial resolution are of paramount importance to probe the full vertical and radial extent of protoplanetary disks. Mapping out their structures and kinematics could allow us to distinguish different disk-shaping mechanisms, including planet–disk interactions, and to link their properties to those of the mature exoplanet populations.

Acknowledgements. We thank the referee Simon Casassus for the constructive feedback, which greatly improved the quality of this paper. This paper makes use of the following ALMA data: 2011.0.00863.S, 2015.1.00806.S, 2016.1.00344.S, and 2018.1.00141.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan) and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. Support for A. F. I. was provided by NASA through the NASA Hubble Fellowship grant No. HST-HF2-51532.001-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555. S.F. acknowledges financial contributions from the European Union (ERC, UNVEIL, 101076613) and from PRIN-MUR 2022YP5ACE. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.

References

- Acke, B., & van den Ancker, M. E. 2006, [A&A](#), **449**, 267
- ALMA Partnership (Brogan, C. L., et al.) 2015, [ApJ](#), **808**, L3
- Ardila, D. R., Golimowski, D. A., Krist, J. E., et al. 2007, [ApJ](#), **665**, 512
- Avenhaus, H., Quanz, S. P., Meyer, M. R., et al. 2014, [ApJ](#), **790**, 56
- Bae, J., & Zhu, Z. 2018a, [ApJ](#), **859**, 118
- Bae, J. & Zhu, Z., 2018b, [ApJ](#), **859**, 119
- Bae, J., Hartmann, L., & Zhu, Z. 2015, [ApJ](#), **805**, 15
- Bae, J., Teague, R., & Zhu, Z. 2021, [ApJ](#), **912**, 56
- Bae, J., Isella, A., Zhu, Z., et al. 2023, in *Astronomical Society of the Pacific Conference Series*, 534, Protostars and Planets VII, eds. S. Inutsuka, Y. Aikawa, T. Muto, K. Tomida, & M. Tamura, 423
- Bate, M. R., Lodato, G., & Pringle, J. E. 2010, [MNRAS](#), **401**, 1505
- Benisty, M., Bae, J., Facchini, S., et al. 2021, [ApJ](#), **916**, L2
- Benisty, M., Dominik, C., Follette, K., et al. 2023, in *Astronomical Society of the Pacific Conference Series*, 534, Protostars and Planets VII, eds. S. Inutsuka, Y. Aikawa, T. Muto, K. Tomida, & M. Tamura, 605
- Beuzit, J. L., Vigan, A., Mouillet, D., et al. 2019, [A&A](#), **631**, A155
- Boccaletti, A., Pantin, E., Lagrange, A. M., et al. 2013, [A&A](#), **560**, A20
- Bohn, A. J., Benisty, M., Perraut, K., et al. 2022, [A&A](#), **658**, A183
- Booth, A. S., Walsh, C., Kama, M., et al. 2018, [A&A](#), **611**, A16
- Booth, A. S., Ilee, J. D., Walsh, C., et al. 2023, [A&A](#), **669**, A53
- Bosman, A. D., Bergin, E. A., Loomis, R. A., et al. 2021, [ApJS](#), **257**, 15
- Brittain, S. D., Najita, J. R., & Carr, J. S. 2009, [ApJ](#), **702**, 85
- Brittain, S. D., Najita, J. R., Carr, J. S., et al. 2013, [ApJ](#), **767**, 159
- Brittain, S. D., Carr, J. S., Najita, J. R., Quanz, S. P., & Meyer, M. R. 2014, [ApJ](#), **791**, 136
- Brittain, S. D., Najita, J. R., & Carr, J. S. 2019, [ApJ](#), **883**, 37
- Casassus, S., & Pérez, S. 2019, [ApJ](#), **883**, L41
- Casassus, S., & Cárcamo, M. 2022, [MNRAS](#), **513**, 5790
- Casassus, S., Pérez, S., Osses, A., & Marino, F. 2019, [MNRAS](#), **486**, L58
- Casassus, S., Christiaens, V., Cárcamo, M., et al. 2021, [MNRAS](#), **507**, 3789
- Casassus, S., Cárcamo, M., Hales, A., Weber, P., & Dent, B. 2022, [ApJ](#), **933**, L4
- Close, L. M., van Capelleveen, R. F., Weible, G., et al. 2025, [ApJ](#), **990**, L9
- Currie, T., Cloutier, R., Brittain, S., et al. 2015, [ApJ](#), **814**, L27
- Currie, T., Brittain, S., Grady, C. A., Kenyon, S. J., & Muto, T. 2017, [RNAAS](#), **1**, 40
- Czekala, I., Loomis, R. A., Teague, R., et al. 2021, [ApJS](#), **257**, 2
- Dullemond, C. P., Küffmeier, M., Goicovic, F., et al. 2019, [A&A](#), **628**, A20
- Ercolano, B., & Pascucci, I. 2017, [Roy. Soc. Open Sci.](#), **4**, 170114
- Espaillet, C., Muzerolle, J., Najita, J., et al. 2014, in *Protostars and Planets VI*, eds. H. Beuther, R. S. Klessen, C. P. Dullemond, & T. Henning, 497
- Facchini, S., Juhász, A., & Lodato, G. 2018, [MNRAS](#), **473**, 4459
- Fedele, D., Toci, C., Maud, L., & Lodato, G. 2021, [A&A](#), **651**, A90
- Flock, M., Ruge, J. P., Dzyurkevich, N., et al. 2015, [A&A](#), **574**, A68
- Flock, M., Nelson, R. P., Turner, N. J., et al. 2017, [ApJ](#), **850**, 131
- Juhász, K. B., Rameau, J., Dong, R., et al. 2017, [AJ](#), **153**, 264
- Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, [PASP](#), **125**, 306
- Gaia Collaboration (Brown, A. G. A., et al.) 2018, [A&A](#), **616**, A1
- Garg, H., Pinte, C., Christiaens, V., et al. 2021, [MNRAS](#), **504**, 782
- Garufi, A., Quanz, S. P., Schmid, H. M., et al. 2016, [A&A](#), **588**, A8
- Grady, C. A., Polomski, E. F., Henning, T., et al. 2001, [AJ](#), **122**, 3396
- Haffert, S. Y., Bohn, A. J., de Boer, J., et al. 2019, [Nat. Astron.](#), **3**, 749
- Hennebelle, P., Lesur, G., & Fromang, S. 2017, [A&A](#), **599**, A86
- Izquierdo, A. F., Facchini, S., Rosotti, G. P., van Dishoeck, E. F., & Testi, L. 2022, [ApJ](#), **928**, 2
- Izquierdo, A. F., Testi, L., Facchini, S., Rosotti, G. P., & van Dishoeck, E. F. 2021, [A&A](#), **650**, A179
- Izquierdo, A. F., Testi, L., Facchini, S., et al. 2023, [A&A](#), **674**, A113
- Izquierdo, A. F., Stadler, J., Galloway-Sprietsma, M., et al. 2025, [ApJ](#), **984**, L8
- Jorsater, S., & van Moorsel, G. A. 1995, [AJ](#), **110**, 2037
- Juhász, A., & Rosotti, G. P. 2018, [MNRAS](#), **474**, L32
- Keppler, M., Benisty, M., Müller, A., et al. 2018, [A&A](#), **617**, A44
- Klahr, H., & Bodenheimer, P. 2004, in *IAU Symposium*, 202, Planetary Systems in the Universe, ed. A. Penny, 350
- Kratter, K., & Lodato, G. 2016, [ARA&A](#), **54**, 271
- Law, C. J., Teague, R., Loomis, R. A., et al. 2021, [ApJS](#), **257**, 4
- Leemker, M., Booth, A. S., van Dishoeck, E. F., et al. 2022, [A&A](#), **663**, A23
- Lesur, G., Hennebelle, P., & Fromang, S. 2015, [A&A](#), **582**, L9
- Lin, D. N. C., & Papaloizou, J. 1979, [MNRAS](#), **188**, 191
- Macintosh, B., Graham, J. R., Ingraham, P., et al. 2014, [PNAS](#), **111**, 12661
- McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in *Astronomical Society of the Pacific Conference Series*, 376, Astronomical Data Analysis Software and Systems XVI, eds. R. A. Shaw, F. Hill, & D. J. Bell, 127
- Miley, J. M., Panić, O., Haworth, T. J., et al. 2019, [MNRAS](#), **485**, 739
- Muley, D., Dong, R., & Fung, J. 2021, [AJ](#), **162**, 129
- Nealon, R., Dipierro, G., Alexander, R., Martin, R. G., & Nixon, C. 2018, [MNRAS](#), **481**, 20
- Norfolk, B. J., Pinte, C., Calcino, J., et al. 2022, [ApJ](#), **936**, L4
- Ogilvie, G. I., & Lubow, S. H. 2002, [MNRAS](#), **330**, 950
- Owen, J. E., Ercolano, B., & Clarke, C. J. 2011, [MNRAS](#), **412**, 13
- Paneque-Carreño, T., Miotello, A., van Dishoeck, E. F., et al. 2022, [A&A](#), **666**, A168
- Paneque-Carreño, T., Pérez, L. M., Benisty, M., et al. 2021, [ApJ](#), **914**, 88
- Paneque-Carreño, T., Miotello, A., van Dishoeck, E. F., et al. 2023, [A&A](#), **669**, A126
- Panić, O., van Dishoeck, E. F., Hogerheijde, M. R., et al. 2010, [A&A](#), **519**, A110
- Pérez, S., Casassus, S., Hales, A., et al. 2020, [ApJ](#), **889**, L24
- Pérez, S., Dunhill, A., Casassus, S., et al. 2015, [ApJ](#), **811**, L5
- Phuong, N. T., Dutrey, A., Di Folco, E., et al. 2020a, [A&A](#), **635**, L9
- Phuong, N. T., Dutrey, A., Diep, P. N., et al. 2020b, [A&A](#), **635**, A12
- Picogna, G., Ercolano, B., Owen, J. E., & Weber, M. L. 2019, [MNRAS](#), **487**, 691
- Pineda, J. E., Szulágyi, J., Quanz, S. P., et al. 2019, [ApJ](#), **871**, 48
- Pinilla, P., Birnstiel, T., & Walsh, C. 2015, [A&A](#), **580**, A105
- Pinte, C., Ménard, F., Duchêne, G., et al. 2018a, [A&A](#), **609**, A47
- Pinte, C., Price, D. J., Ménard, F., et al. 2018b, [ApJ](#), **860**, L13
- Pinte, C., van der Plas, G., Ménard, F., et al. 2019, [Nat. Astron.](#), **3**, 1109

- Pinte, C., Teague, R., Flaherty, K., et al. 2023, in [Astronomical Society of the Pacific Conference Series](#), 534, Protostars and Planets VII, eds. S. Inutsuka, Y. Aikawa, T. Muto, K. Tomida, & M. Tamura, 645
- Pinte, C., Ilee, J. D., Huang, J., et al. 2025, [ApJ](#), 984, L15
- Pyrin, M. A., Delage, T. N., Kurtovic, N. T., et al. 2021, [A&A](#), 656, A150
- Quanz, S. P., Amara, A., Meyer, M. R., et al. 2013, [ApJ](#), 766, L1
- Quanz, S. P., Amara, A., Meyer, M. R., et al. 2015, [ApJ](#), 807, 64
- Rafikov, R. R. 2002, [ApJ](#), 569, 997
- Rice, W. K. M., Armitage, P. J., Bate, M. R., & Bonnell, I. A. 2003, [MNRAS](#), 338, 227
- Riols, A., & Lesur, G. 2019, [A&A](#), 625, A108
- Rosotti, G. P., Benisty, M., Juhász, A., et al. 2020, [MNRAS](#), 491, 1335
- Rosotti, G. P., Ilee, J. D., Facchini, S., et al. 2021, [MNRAS](#), 501, 3427
- Sakai, N., Hanawa, T., Zhang, Y., et al. 2019, [Nature](#), 565, 206
- Sanchis, E., Picogna, G., Ercolano, B., Testi, L., & Rosotti, G. 2020, [MNRAS](#), 492, 3440
- Sissa, E., Gratton, R., Garufi, A., et al. 2018, [A&A](#), 619, A160
- Stadler, J., Benisty, M., Izquierdo, A., et al. 2023, [A&A](#), 670, L1
- Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, [AJ](#), 97, 1451
- Teague, R. 2019, [J. Open Source Softw.](#), 4, 1632
- Teague, R., & Foreman-Mackey, D. 2018, [RNAAS](#), 2, 173
- Teague, R., Bae, J., Bergin, E. A., Birnstiel, T., & Foreman-Mackey, D. 2018, [ApJ](#), 860, L12
- Teague, R., Bae, J., & Bergin, E. A. 2019a, [Nature](#), 574, 378
- Teague, R., Bae, J., Huang, J., & Bergin, E. A. 2019b, [ApJ](#), 884, L56
- Teague, R., Bae, J., Aikawa, Y., et al. 2021, [ApJS](#), 257, 18
- Teague, R., Bae, J., Andrews, S. M., et al. 2022a, [ApJ](#), 936, 163
- Teague, R., Bae, J., Benisty, M., et al. 2022b, [ApJ](#), 930, 144
- Teague, R., Benisty, M., Facchini, S., et al. 2025, [ApJ](#), 984, L6
- Thies, I., Kroupa, P., Goodwin, S. P., Stamatellos, D., & Whitworth, A. P. 2011, [MNRAS](#), 417, 1817
- Uribe, A., Matsakos, T., & Konigl, A. 2015, in [Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun](#), 18, 18th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, 739
- van Capelleveen, R. F., Ginski, C., Kenworthy, M. A., et al. 2025, [ApJ](#), 990, L8
- van der Marel, N., van Dishoeck, E. F., Bruderer, S., et al. 2016, [A&A](#), 585, A58
- Walsh, C., Juhász, A., Pinilla, P., et al. 2014, [ApJ](#), 791, L6
- Walsh, C., Daley, C., Facchini, S., & Juhász, A. 2017, [A&A](#), 607, A114
- Weaver, E., Isella, A., & Boehler, Y. 2018, [ApJ](#), 853, 113
- Wölfer, L., Facchini, S., Kurtovic, N. T., et al. 2021, [A&A](#), 648, A19
- Wölfer, L., Facchini, S., van der Marel, N., et al. 2023, [A&A](#), 670, A154
- Zhang, S., Zhu, Z., Huang, J., et al. 2018, [ApJ](#), 869, L47

Appendix A: Comparison of the ^{12}CO 3-2 datasets

Here, we compare the individual short and long-baseline datasets of ^{12}CO 3-2 to the combined data to assess if artificial features might have been introduced in the imaging process. The overall patterns are consistent among the dataset, supporting the robustness of our results.

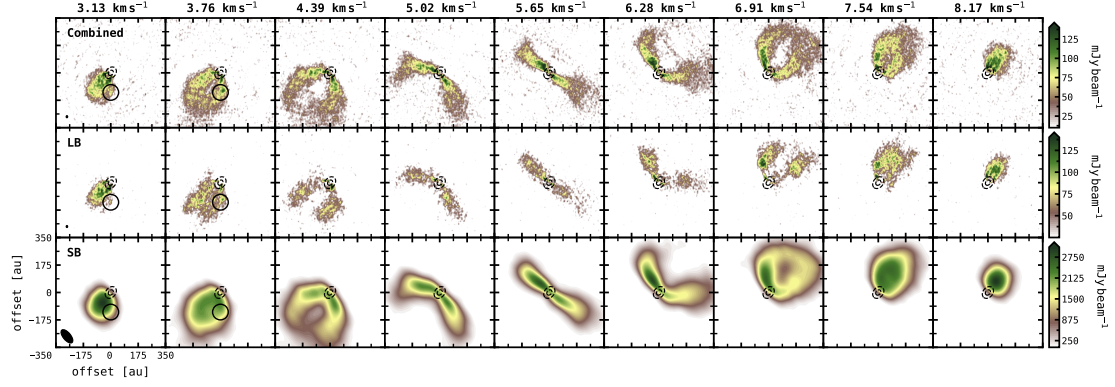


Fig. A.1. Comparison of the different ^{12}CO 3-2 datasets, with the combined data in the top, the long-baseline data in the middle, and the short-baseline data in the bottom row. Shown are the channels in steps or three from the central channel and for a velocity resolution of 210 m s^{-1} . The inner mm continuum ring is overlaid as dashed contours. A localized feature is seen in some of the channels within the solid circle. The observational beam is shown in the bottom left corner of the first panel of each row.

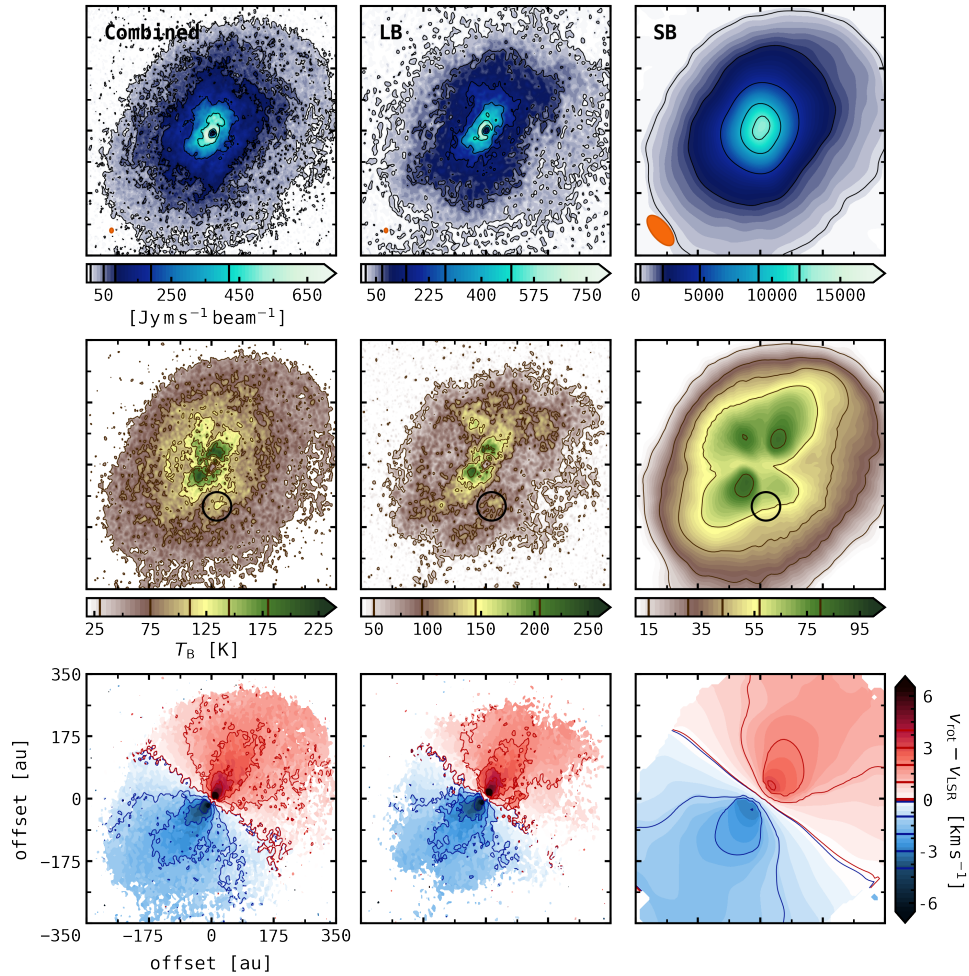


Fig. A.2. Comparison of the different ^{12}CO 3-2 datasets, with the combined data in the left, the long-baseline data in the middle, and the short-baseline data in the right column. Shown are the integrated intensity (top), peak intensity (middle), and line-of-sight velocity (bottom). A localized feature is highlighted by the solid circle. Some contours are overlaid and their levels are indicated in the color bars. The observational beam is shown in the bottom left corner of the first-row panels.

Appendix B: Full data cubes

In this section, we report the full data cubes used in the analysis, showing the whole intensity range.

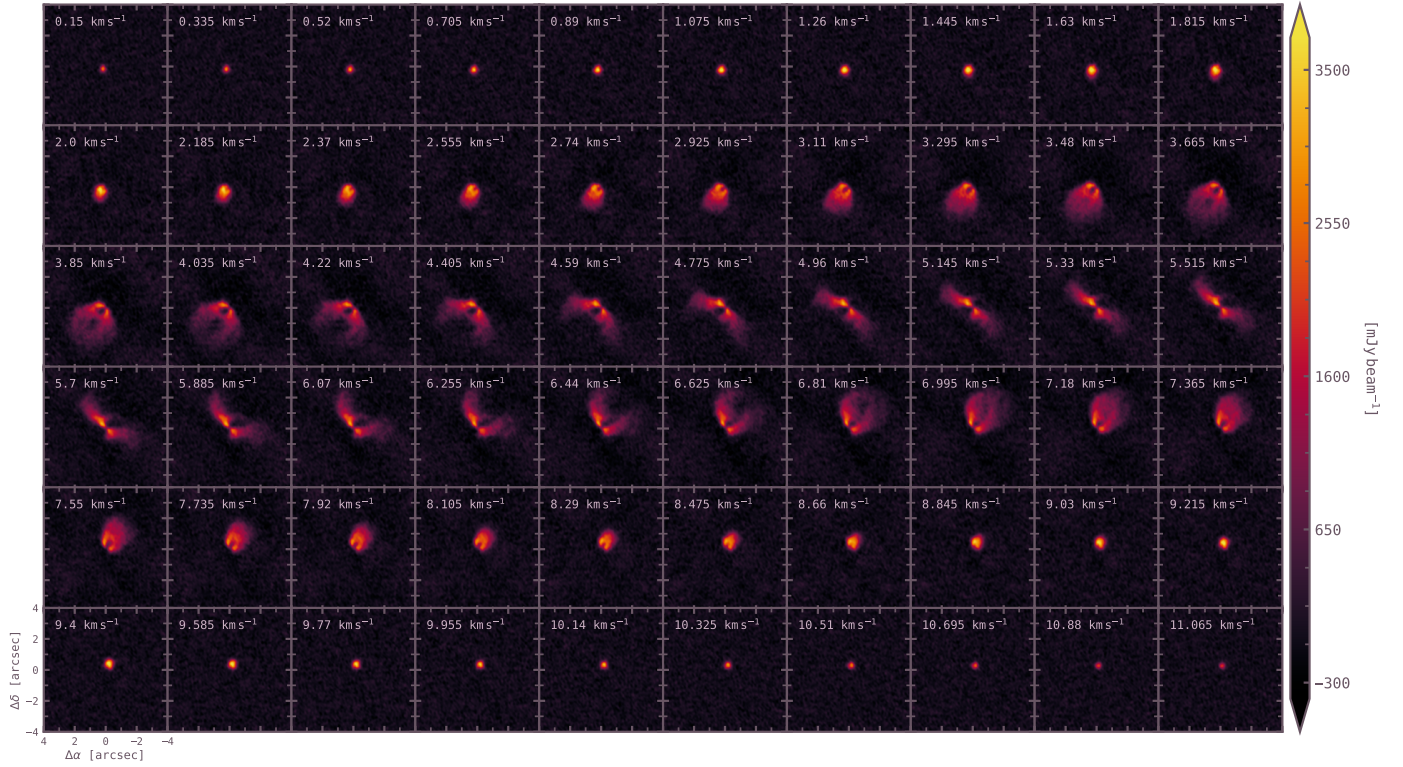


Fig. B.1. Intensity maps of the full data cubes, shown for the ^{12}CO 7-6 emission line.

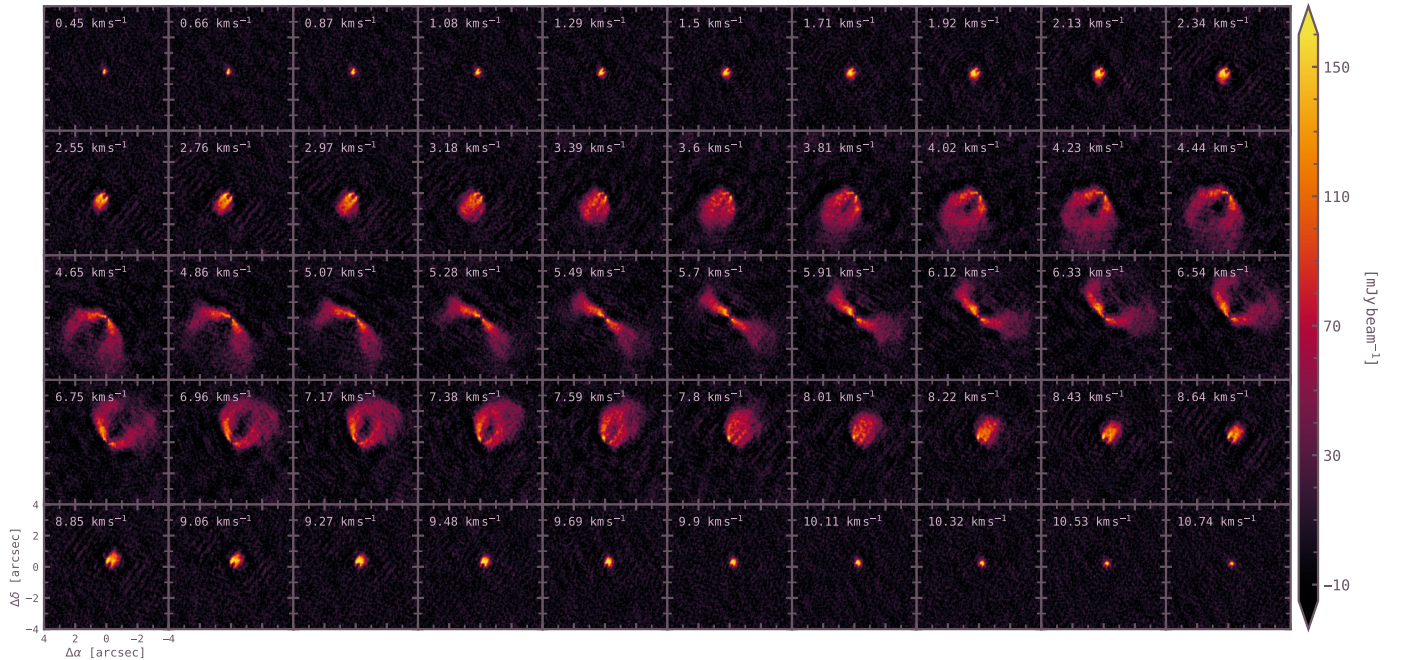


Fig. B.2. Intensity maps of the full data cubes, shown for the ^{12}CO 3-2 emission line.

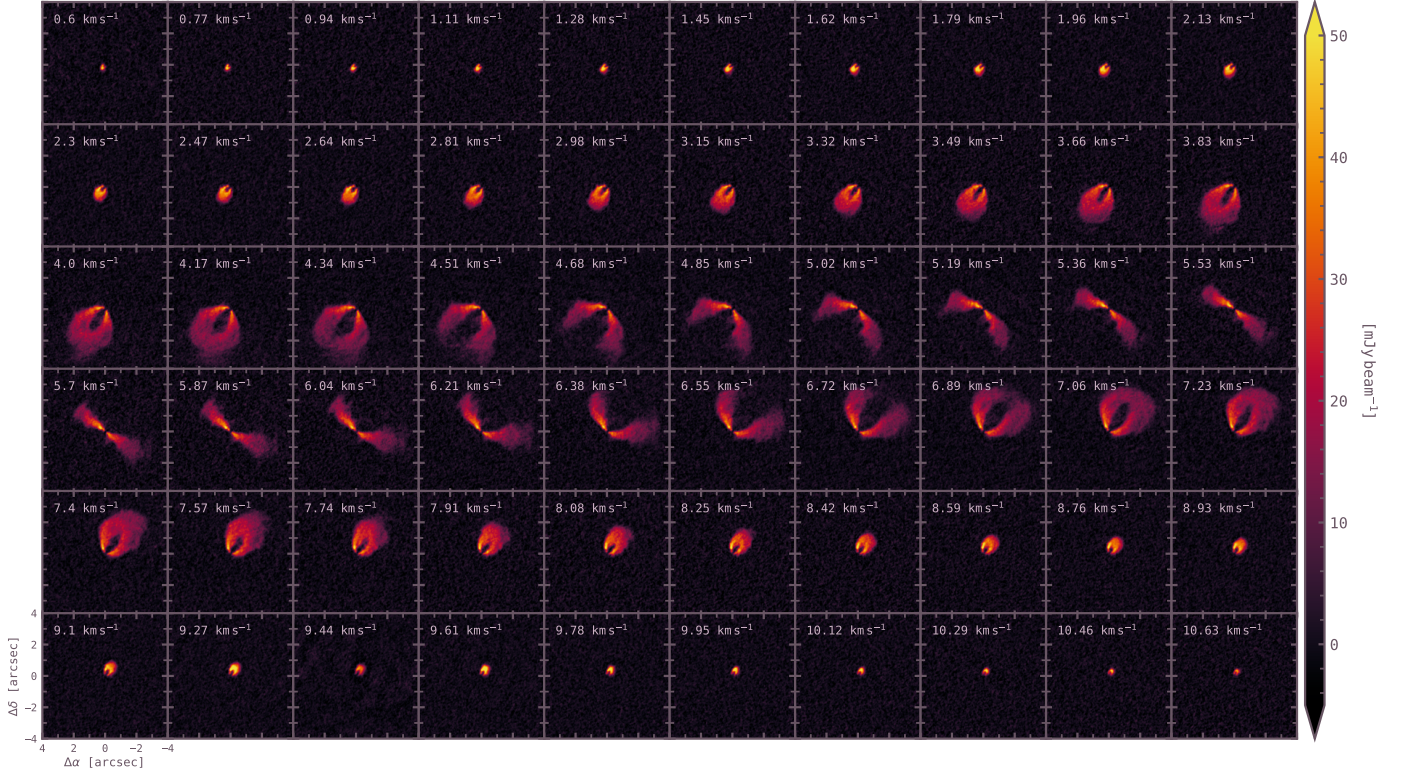


Fig. B.3. Intensity maps of the full data cubes, shown for the ^{12}CO 2-1 emission line.

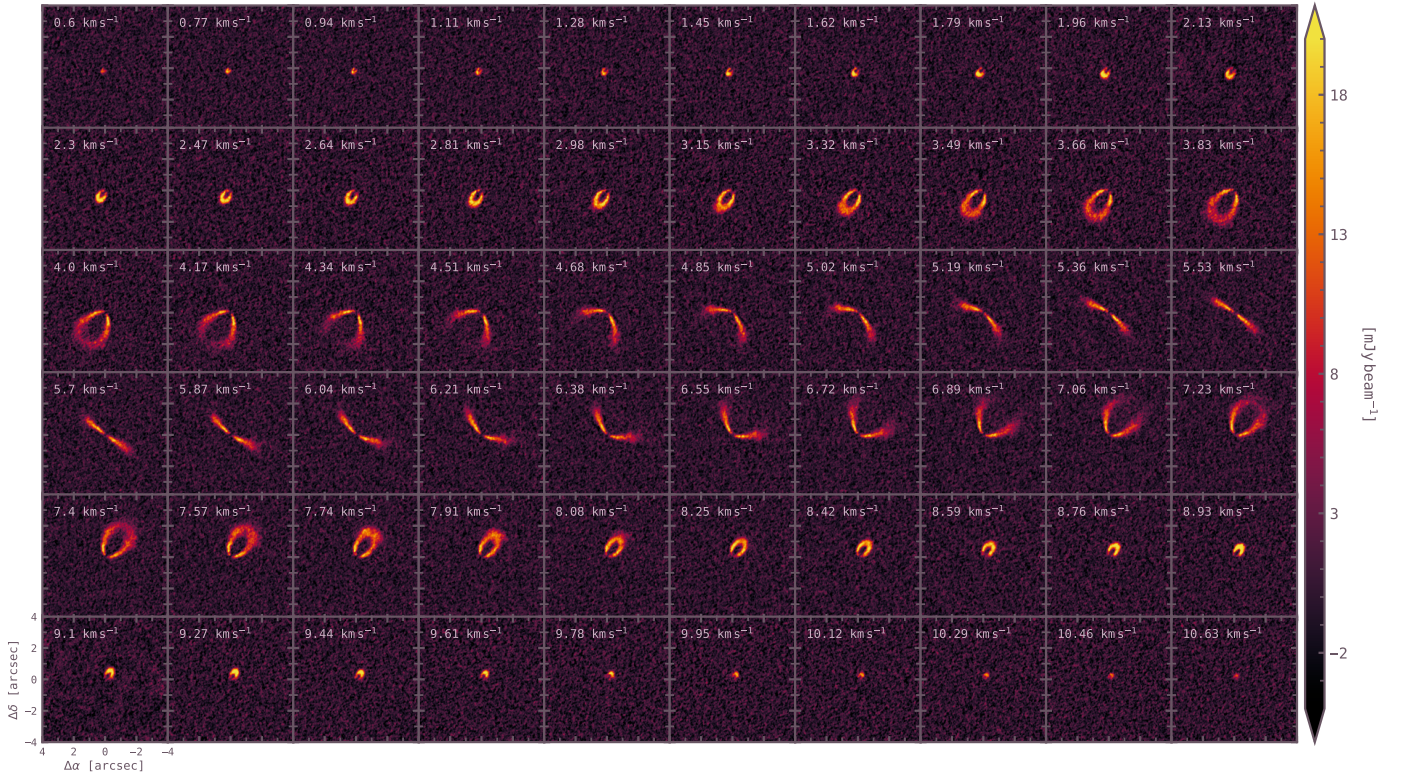


Fig. B.4. Intensity maps of the full data cubes, shown for the ^{13}CO 2-1 emission line.

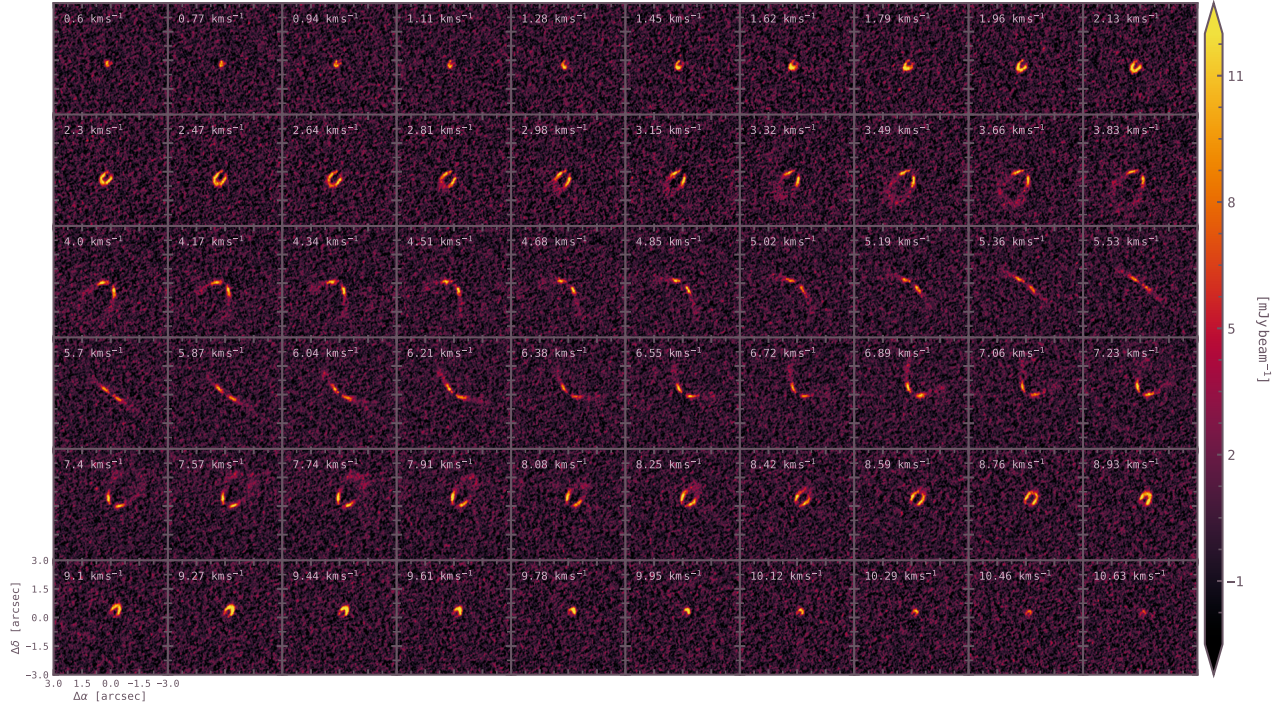


Fig. B.5. Intensity maps of the full data cubes, shown for the C¹⁸O 2-1 emission line.

Appendix C: Best-fit parameters for the blue and red-shifted cube

Table C.1. Best-fit results of the modelling of the blueshifted channels with the DISCMINER^(a).

Attribute	Parameter	Unit	¹² CO 7-6	¹² CO 3-2	¹² CO 2-1	¹³ CO 2-1	C ¹⁸ O 2-1
Orientation	x_c	au	-1.67	7.20	0.25	3.23	3.92
	y_c	au	6.71	-11.12	-2.52	-0.82	-2.63
Velocity	M_*	M _⊙	2.07	1.99	2.06	2.13	2.26
	v_{sys}	km s ⁻¹	5.43	5.66	5.69	5.66	5.69
Upper surface	z_0	au	162.87	25.87	19.00	5.97	8.12
	p	-	3.69	0.55	0.67	0.03	0.31
	q	-	2.29	5.00	4.99	3.22	2.47
	R_t	au	71.47	362.98	364.27	111.69	134.29
Lower surface	z_0	au	11.64	20.20	34.04	17.84	-
	p	-	0.05	1.69	1.78	1.48	-
	q	-	4.99	1.06	0.92	4.34	-
	R_t	au	143.90	181.40	123.35	18.23	-
Intensity	I_0	Jy px ⁻¹	1.67	1.00	0.99	0.03	0.01
	p_0	-	0.90	0.36	-0.44	1.02	0.99
	p_1	-	-1.00	-0.96	-1.39	-0.29	-2.31
	q	-	0.03	0.71	1.22	0.07	0.001
	R_{break}	au	46.75	41.89	47.93	59.55	63.67
	R_{out}	au	347.70	438.16	393.23	296.01	247.79
Line width	L_W	km s ⁻¹	0.87	0.74	0.67	0.36	0.10
	p	-	-0.32	-0.58	-0.59	-0.91	-1.09
	q	-	0.02	-0.04	0.03	-0.03	-0.35
Line slope	L_S	-	2.00	2.22	2.16	1.86	1.86
	p	-	0.33	0.07	0.15	-0.03	0.05

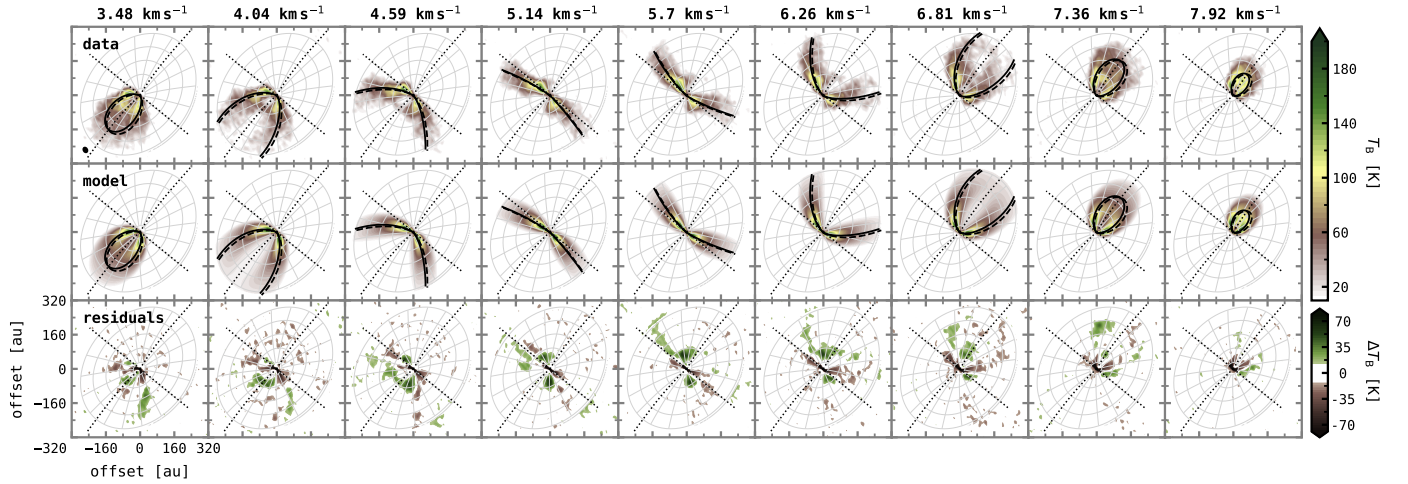
Notes. ^(a)The inclination and position angle were fixed to the values obtained for the full ¹²CO cube.

Table C.2. Best-fit results of the modeling of the redshifted channels with the DISCMINER^(a).

Attribute	Parameter	Unit	¹² CO 7-6	¹² CO 3-2	¹² CO 2-1	¹³ CO 2-1	C ¹⁸ O 2-1
Orientation	x_c	au	1.70	4.30	-2.10	-0.67	1.93
	y_c	au	-0.92	-9.05	-1.90	-1.53	-4.95
Velocity	M_*	$M_\odot$	1.99	2.15	2.10	2.10	2.32
	v_{sys}	km s^{-1}	5.34	5.57	5.59	5.64	5.58
Upper surface	z_0	au	26.33	25.06	13.68	5.67	12.17
	p	-	1.05	0.77	1.33	0.32	0.60
	q	-	4.96	4.99	8.45	4.99	1.97
	R_t	au	295.22	335.88	319.70	244.50	196.19
Lower surface	z_0	au	33.91	14.62	13.06	3.41	-
	p	-	1.87	1.28	2.02	0.33	-
	q	-	1.15	1.22	1.23	4.84	-
	R_t	au	154.22	387.04	250.44	151.36	-
Intensity	I_0	Jy px^{-1}	9.97	1.00	0.64	0.10	0.01
	p_0	-	-1.03	0.55	-0.24	0.44	1.60
	p_1	-	-1.95	-1.06	-1.51	-0.68	-2.27
	q	-	1.04	0.59	0.73	0.50	0.002
	R_{break}	au	53.31	42.92	46.73	64.54	60.65
	R_{out}	au	330.38	394.28	369.76	344.66	247.20
Line width	L_W	km s^{-1}	1.04	0.67	0.43	0.27	0.02
	p	-	-0.92	-0.48	-0.35	-0.61	-0.81
	q	-	0.25	-0.10	-0.21	-0.11	-1.24
Line slope	L_S	-	2.51	2.06	2.25	1.74	1.95
	p	-	0.12	0.17	0.32	0.001	0.02

Notes. ^(a)The inclination and position angle were fixed to the values obtained for the full ¹²CO cube.

Appendix D: Comparison of the data and model channels


Fig. D.1. Same as in Fig. 5 but for ¹²CO 7-6.

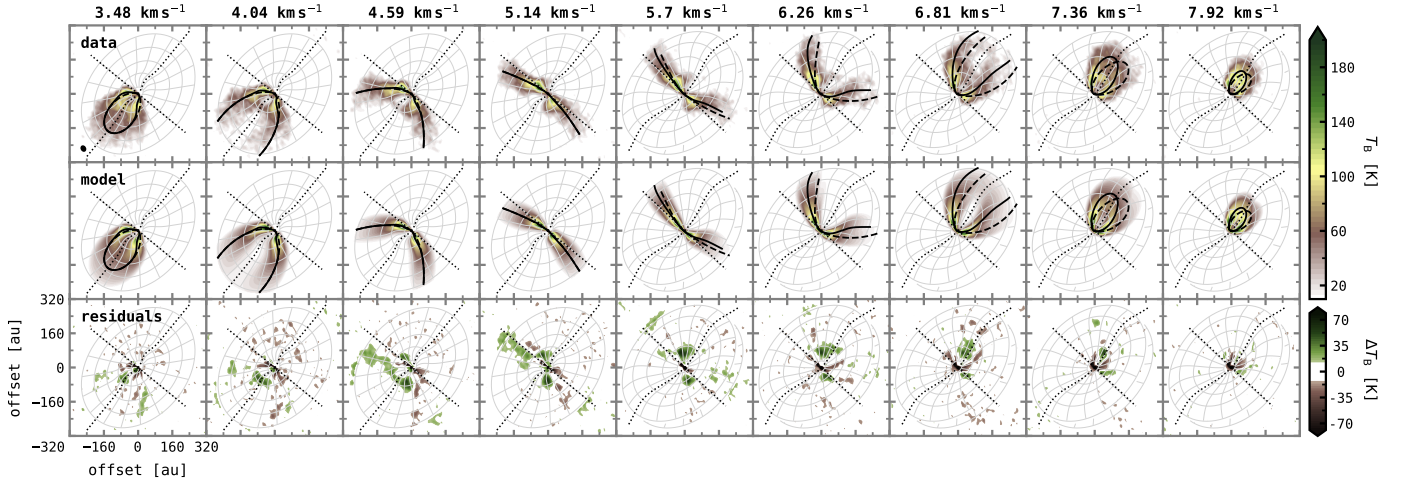


Fig. D.2. Same as in Fig. 5 but for ^{12}CO 7-6 and the blue- and redshifted sides being modeled separately.

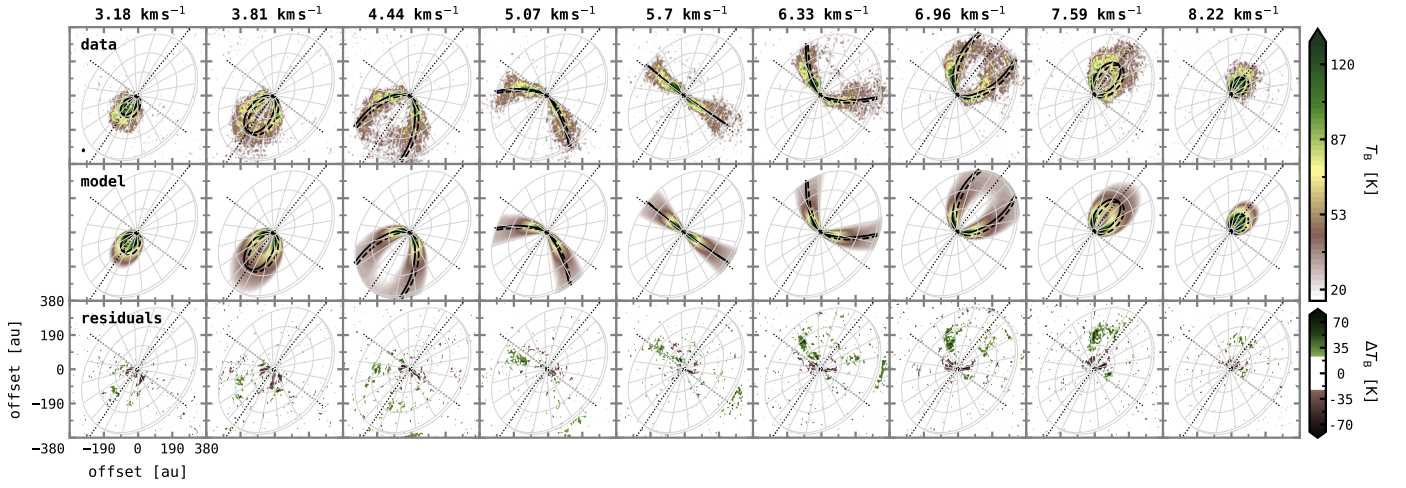


Fig. D.3. Same as in Fig. 5 but for ^{12}CO 3-2.

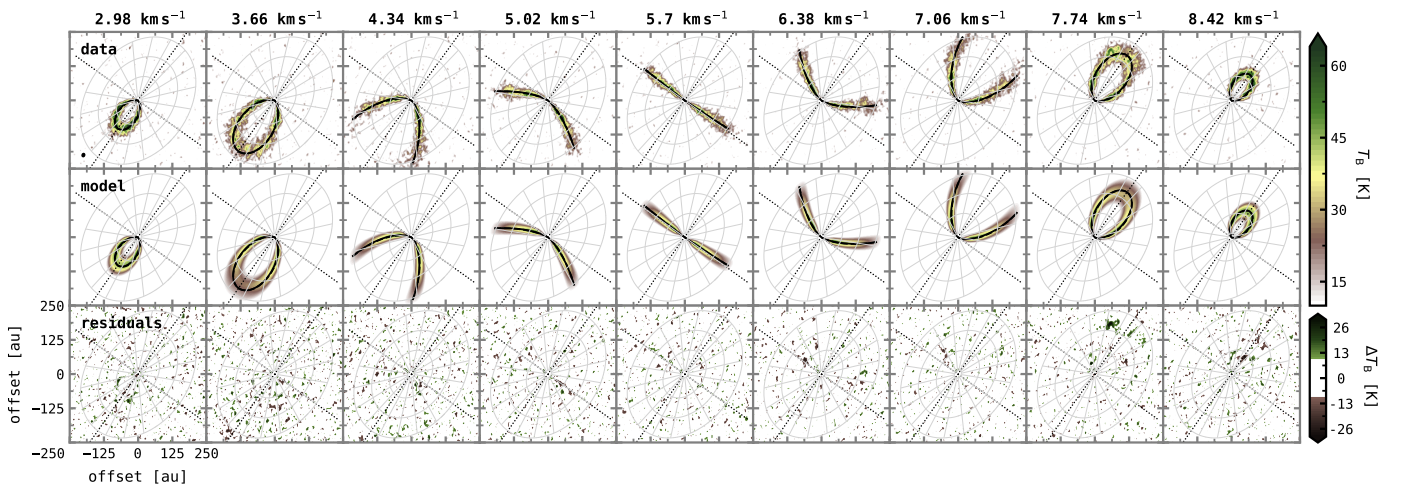


Fig. D.4. Same as in Fig. 5 but for ^{13}CO 2-1.

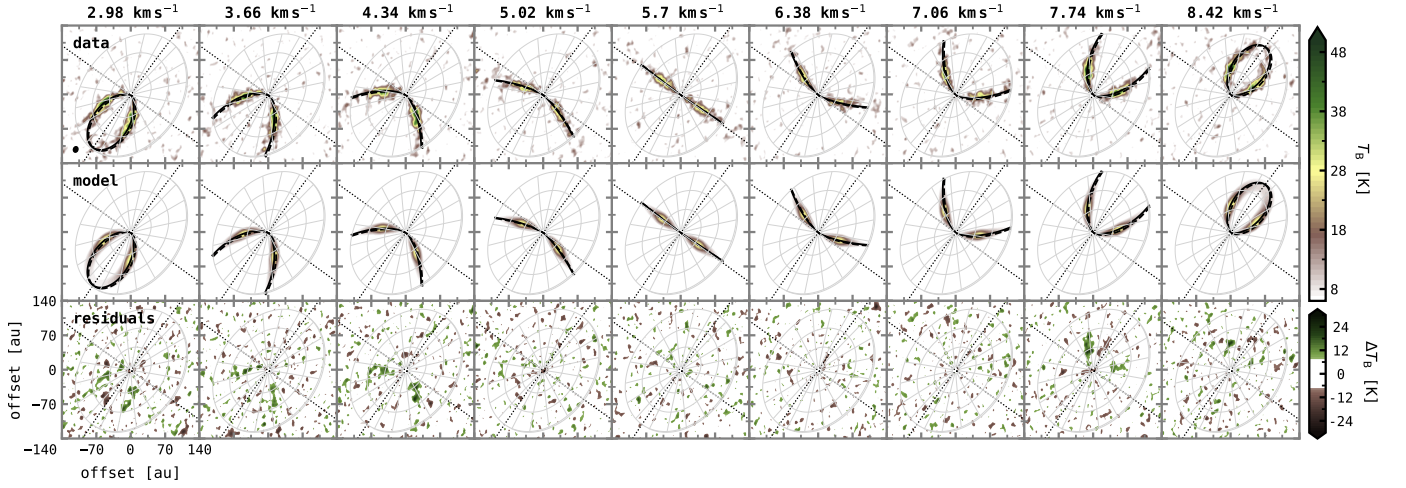


Fig. D.5. Same as in Fig. 5 but for C¹⁸O 2-1.

Appendix E: Logarithmic spirals

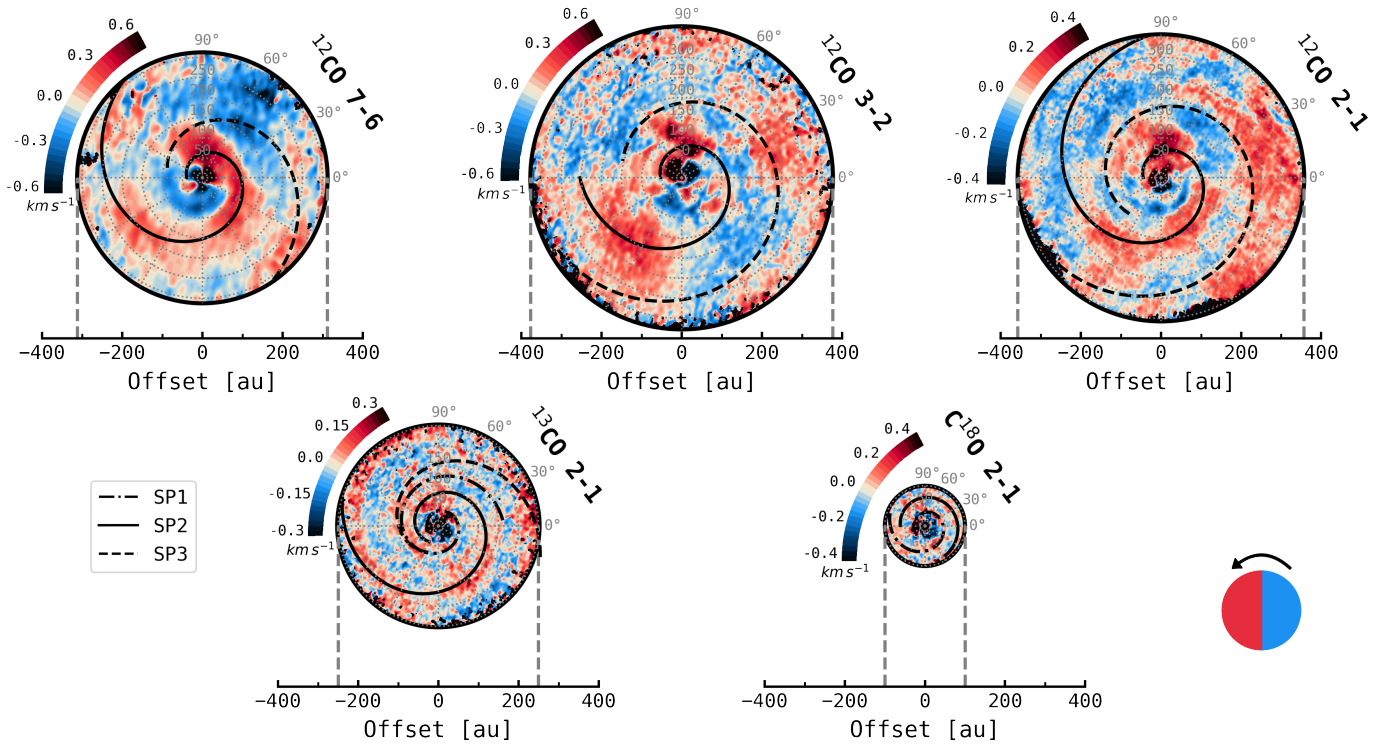


Fig. E.1. Same as in Fig. 7 but with overlaid logarithmic spirals.

Appendix F: Peak intensity and line width residuals

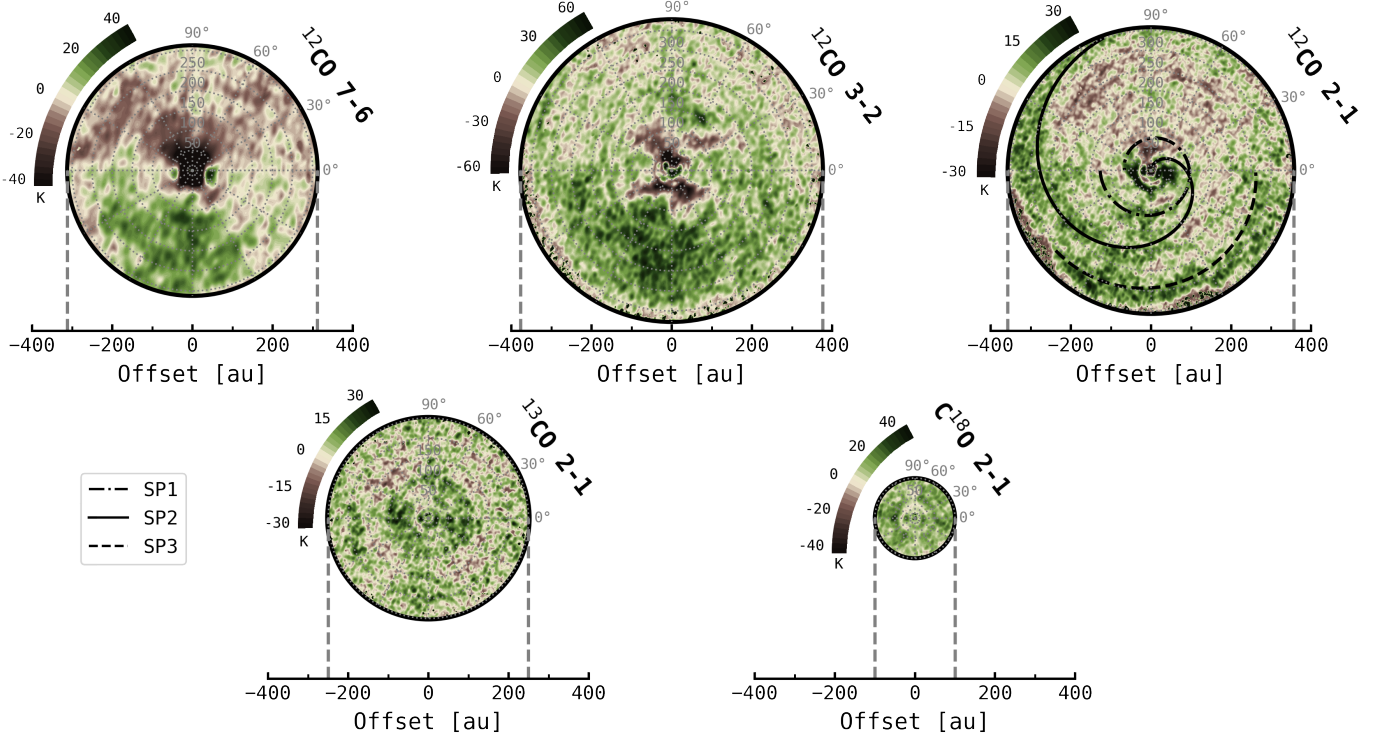


Fig. F.1. Peak intensity residuals, shown for the five lines studied in this work.

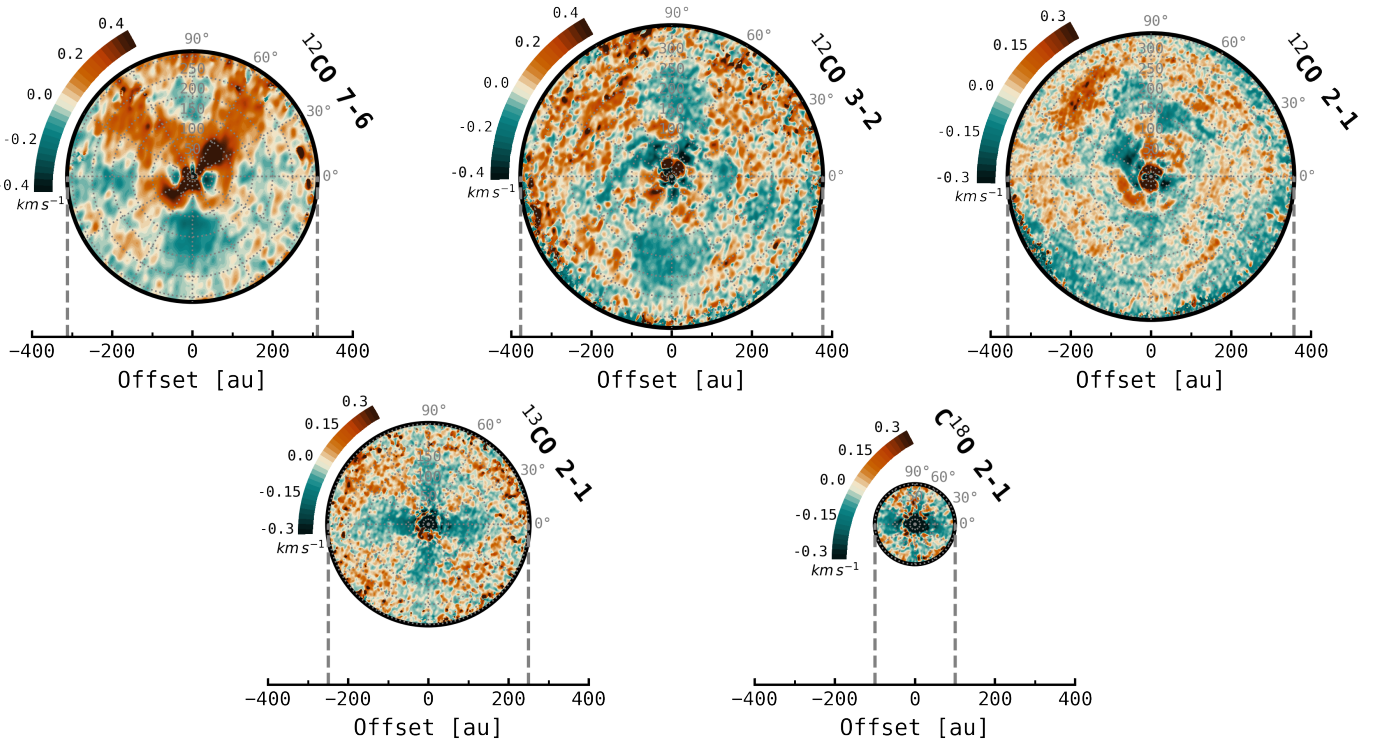


Fig. F.2. Line width residuals, shown for the five lines studied in this work.

Appendix G: JvM-corrected data

In this section, we include some of the results for the JvM corrected data. This method (Jorsater & van Moorsel 1995; Czekala et al. 2021) aims to correct for imaging artifacts induced by the non-Gaussianity of the dirty beam. The resulting epsilon values, the ratio of the CLEAN beam volume to the dirty beam volume, are given as 0.56 for Band 6 and 0.22 for Band 7. However, caution needs to be exercised when using the JvM correction (Casassus & Cárcamo 2022), and thus we conducted our full analysis on both the corrected and non-corrected datasets. We find that our results are robust irrespective of the choice of using the JvM correction in the imaging process, with the difference that the non-corrected data have artificially lower noise levels by factors of 1/0.56 (Band6) and 1/0.22 (Band7), which affects mainly the patterns in the outer disk regions. The trends and substructures described in the main body of the paper are the same, yet the JvM-correction is appealing as it helps to smooth the data and make it easier to discern the patterns. Altogether, our conclusions are not affected by the use of the JvM-correction.

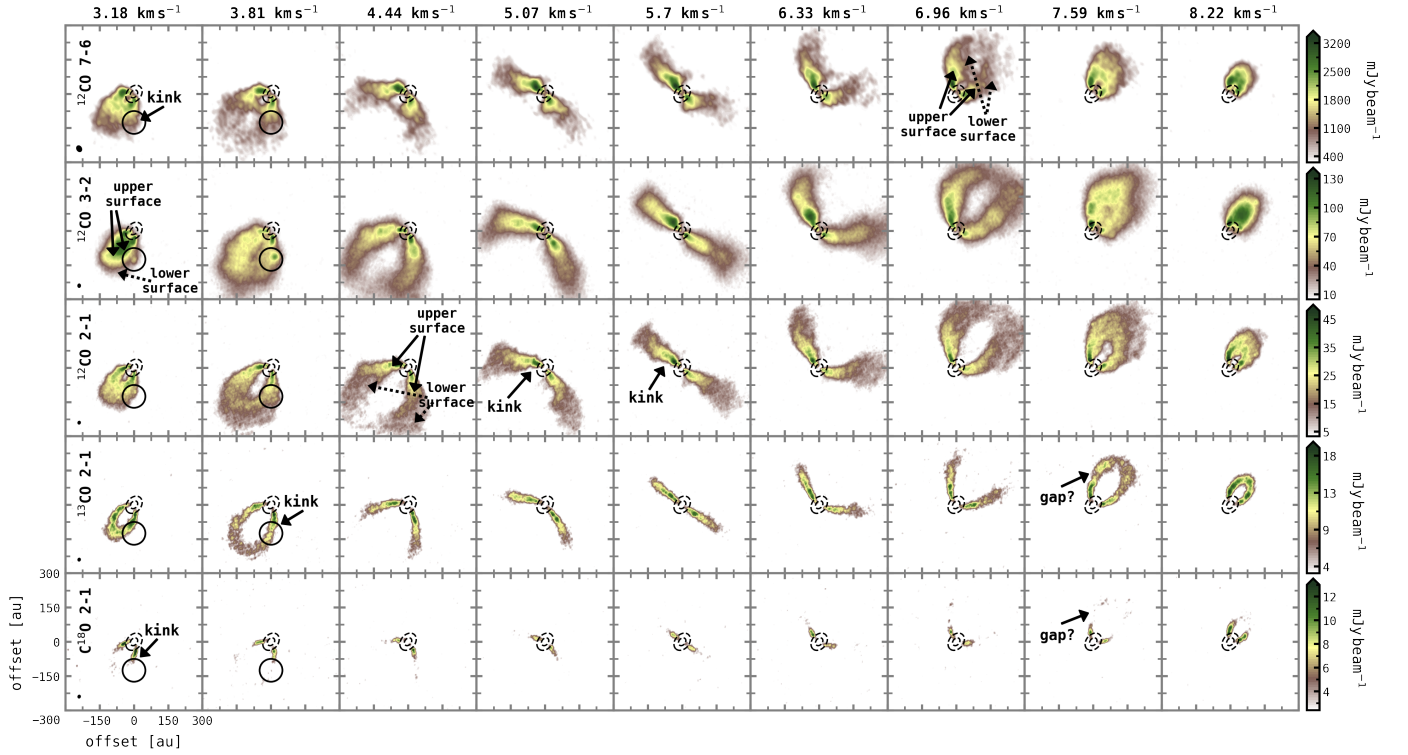


Fig. G.1. Same as Fig. 2 but for the JvM-corrected data.

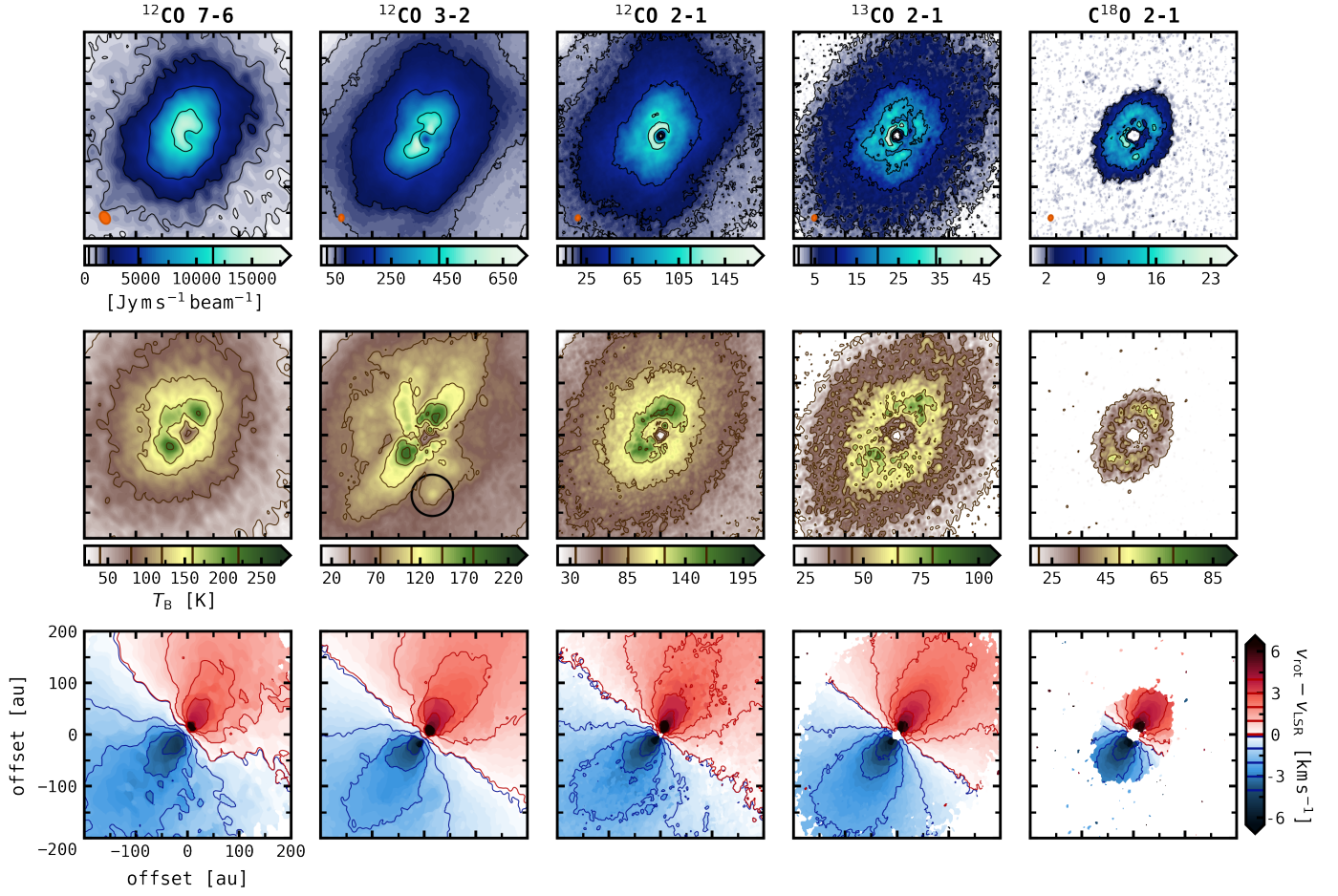


Fig. G.2. Same as Fig. 3 but for the JvM-corrected data.

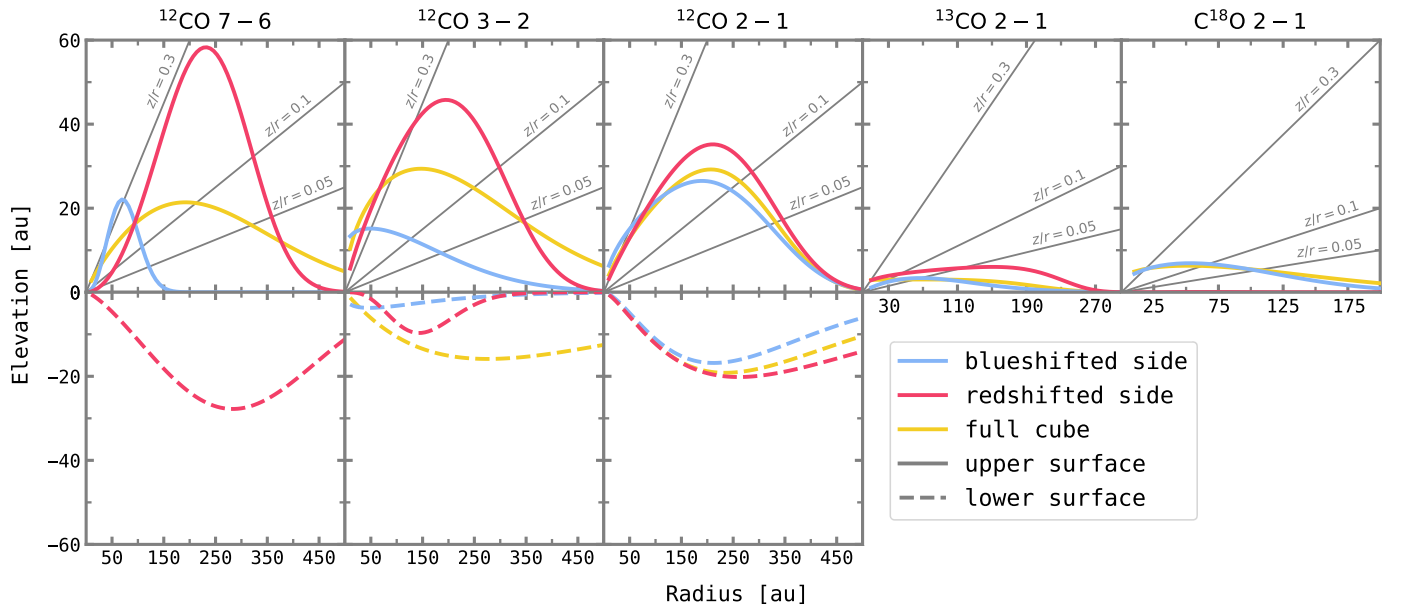


Fig. G.3. Same as Fig. 11 but for the JvM-corrected data.

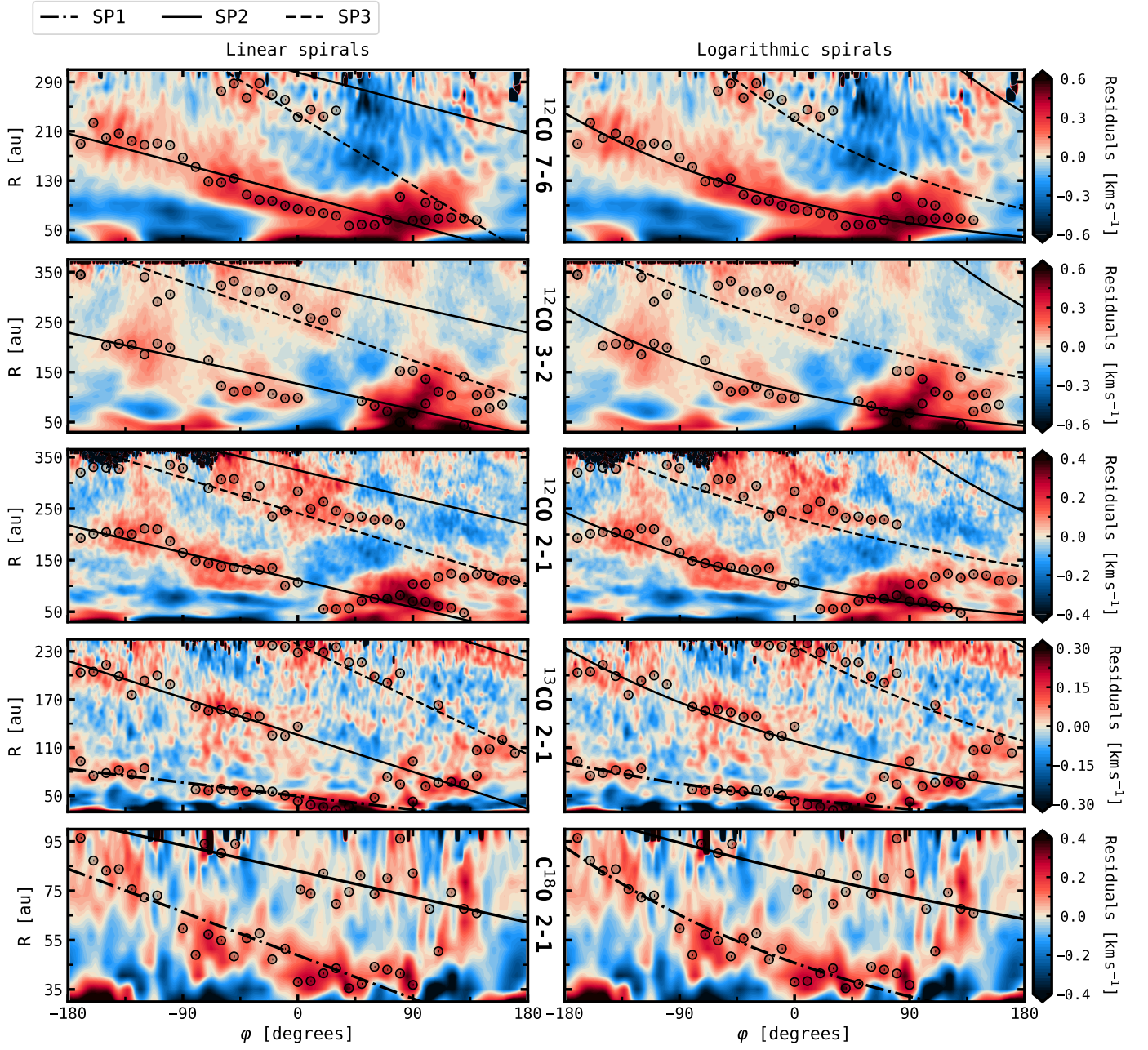


Fig. G.4. Same as Fig. 8 but for the JvM-corrected data.