PLANET-GAS INTERACTIONS IN DEBRIS DISKS: OBSERVABLE STRUCTURES

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Abstract. Since recently, consequent amounts of CO gas were observed in old debris disks which were expected to be gas-free. At this stage, planet formation already occurred and planets are expected to be evolving in these discs. In this presentation, we show how these planets might form observable substructures in the gas of these debris disks. We focus specifically on a recent method developed in protoplanetary disks: when a planet is embedded in a gas disk, it perturbs its normally keplerian velocity, forming a kink. By simulating an already known debris disk hosting a large amount of CO, we show that these features can also be observed in debris disks. This leads to a new way to indirectly detect exoplanets and to better characterize the interactions between the already formed planets and the old observed gas.

Keywords: debris disks, synthetic observations, CO gas, planet-gas interactions, kinks

1 Introduction

1.1 Substructures observed in protoplanetary disks and their origin

Planets form in gas-rich (99% of gas for 1% of dust) disks surrounding new-born stars. Recent ALMA observations of the birth environment of planets show different kinds of substructures, like gaps, rings or asymmetries, both in the dust (e.g., as seen in the analysis from the DSHARP survey, Huang et al. 2018) and in the gas (e.g., in the CO distribution of the MAPS survey, Zhang et al. 2021). Simulations show that these substructures might have several different origins, as for example, zonal flows (Flock et al. 2015), secular gravitational instabilities (Takahashi & Inutsuka 2016; Tominaga et al. 2020) or sintering-induced rings (Okuzumi et al. 2016).

Another possible origin for these substructures is from the interactions between growing planets and their birth environment (e.g., Zhang et al. 2018; Teague et al. 2021). However, it is complicated to directly detect these planets due to the very dusty environment around them (Sanchis et al. 2020), forcing us to rely on the indirect impact that the planets leave on their environment.

When planets are embedded in their gaseous disks, they can create gaps if they are massive enough but also spiral arms, due to resonances with the gas in differential rotation. The characteristics of the spiral arms depend on the properties of both the planet and the gas. They impact the rotational velocity of the gas, which normally follows a keplerian profile. These deviations from the keplerian profiles are called **kinks** (for a review see Pinte et al. 2022). As shown in Fig.1, they are the strongest at the planet location and then dissipate in amplitude further away in the disk. It is possible to observe the velocity structure of disks thanks to the Doppler effect, making these kinks observable. They can therefore help to indirectly detect planets which are not massive enough to open a deep gap and/or to determine if a gap is indeed linked to the presence of a planet or not.

These kinks have been observed in CO gas by ALMA on multiple occasions: for example, in Pinte et al. (2018), they detected a perturbation of the gas rotational velocity in HD163296, consistent with a two-Jupiter-mass planet located at ≈ 260 AU from its host star. In Teague et al. (2018), they find two other deviations from the keplerian rotation of CO isotopologues, consistent with the presence of two Jupiter mass planets located at ≈ 83 and 137 AU. More recently, in Stadler et al. (2023), they find a non-keplerian feature in RXJ1604.3-2130A, consistent with a planet of $\approx 2\ \mathrm{M_J}$ located at roughly 41 AU. These detections prove that ALMA has the capacity to find such perturbations of the rotational velocity in a gaseous disk.

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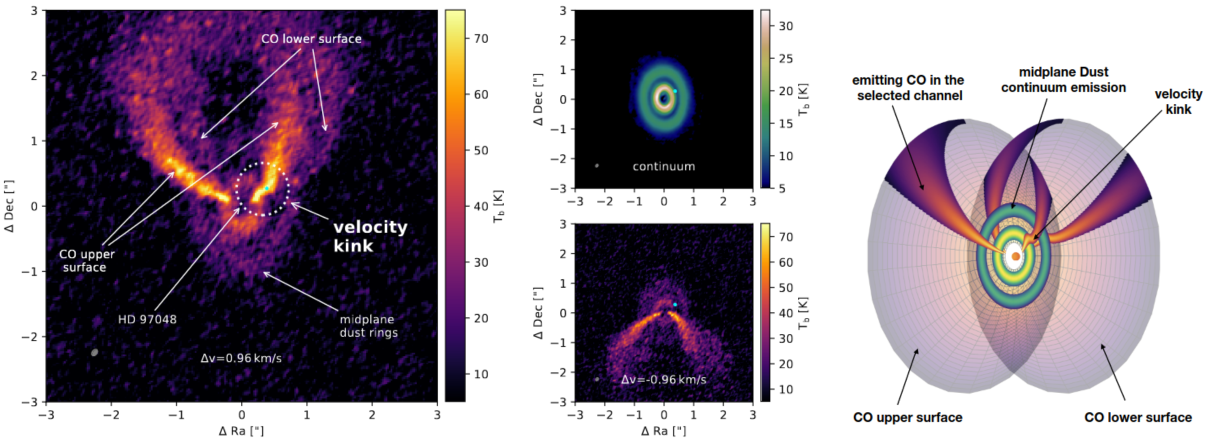

Fig. 1. From Pinte et al. (2019): **Left:** ALMA observations of the dust and gas disc surrounding HD 97048. a) ^{13}CO 3-2 emission at velocity $+0.96\text{km.s}^{-1}$ from the systemic velocity. The velocity kink revealing the presence of an embedded perturber is marked by a dotted circle and the cyan dot represents the location of the putative planet. The kink is located above the gap detected in continuum.b) 885 μm continuum emission using all the continuum channels b) and c) ^{13}CO 3-2 emission at the opposite velocity $-0.96\text{km.s}^{-1}$from the systemic velocity, where the emission displays a smooth profile. Line observations were not continuum subtracted. The ALMA beam is 0.07" $\times$ 0.11" and is indicated by the grey ellipse. **Right:** Schematic view of the disc as seen by ALMA in a single channel. The CO emission originates from the disc surfaces, while the continuum is mostly emitted from the disc midplane.

1.2 Observed CO rich gas during the debris disk phase

The gaseous phase of the protoplanetary disk is estimated to last up to 10 Myrs due to different dispersal mechanisms (e.g., viscous accretion, disk winds, photoevaporation, see review by Lesur et al. 2022). After then, the system becomes a debris disk, mostly composed of dust, planetesimals and the formed planets. Since recently, gas has been observed in these old disks too (e.g., Moór et al. 2017). This gas seems to be highly enriched in metals compared to protoplanetary disks with the gas abundances being dominated by CO, C and O. Some models suggest that this might indicate that the gas is not primordial and originates from the collision of planetesimals (Kral et al. 2019) . It could then viscously evolve similarly to the protoplanetary disk phase, perhaps through an efficient MRI effect thanks to the high ionisation rate present in debris disks (Kral & Latter 2016). Some of the observed debris disks can host up to a few tenth of Earth masses in CO gas (Cataldi et al. 2020), similar to the amount of CO seen in some protoplanetary disks (Zhang et al. 2021).

2 Applying CO kinks analysis to debris disks

While we have some direct observations of planets in debris disks - as for example in the β Pictoris system, hosting a 9 M_J planet at 2.7 AU and a 10 M_J planet at 9.2 AU (Lagrange et al. 2019) or in the GJ504 system, hosting a 4 M_J planet at around 43 AU (Bonnefoy et al. 2018) - the direct detection method is able to probe mostly the most massive (and therefore more luminous) planets with masses larger than a few Jupiter masses. The debris disks might host smaller planets that cannot be observed directly. However, these hidden planets might interact with their surrounding environment and leave characteristic substructures that we can observe, such as the CO kinks observed in the protoplanetary disks. As the amount of CO observed in the debris disks is similar to some protoplanetary disks, we show here that such kinks can be observed in debris disks too.

Applying this analysis to the gas present in debris disks can lead to a new way to detect exoplanets, at an intermediate stage during the life of the planetary system where the majority of the primordial gas is gone but the planetesimal belts are still massive. In case of detection, we can start to then characterize then the interactions between the planets and this CO enriched gas: indeed, if this gas can approach the planets, then it might be accreted by them too, enriching their metallicity compared to the metallicity of the host star, as investigated by Kral et al. (2020).

2.1 The example of HD138813

As mentioned earlier, the CO kinks depend on the properties of both the planet and the gas. In order to test if such kinks are indeed observable in debris disk-like conditions, we based part of our study on a known debris disk. We selected a luminous and massive disk where CO was already detected and characterized: the disk around HD138813 (A0V star, located at 137.5 pc). Thanks to the analysis of previous observations, the disk around HD138813 is expected to host a quite significant mass of CO gas ($\sim 3\times10^{-3}$ $M_\oplus$, Hales et al. 2019). Its CO ring is estimated to spread between 5 AU and 210 AU, with a surface density profile constrained to follow $\Sigma_0(65\ \mathrm{AU}) = 10^{-5}\mathrm{g/cm}^2$ with a power law profile in $r^{-0.5}$ for the inner part ($r < 65$ AU) and in $r^{-4.0}$ for the outer part ($r > 65$ AU).

The advantage of HD138813 is its intermediate inclination (29° with a polar angle of 49.6°), which allows us to have a good representation of the isovelocities geometry (Pinte et al. 2022). It exists more massive disks that are more luminous than HD138813, however their inclination does not fit our constraints (such as HD32297 for example, with an estimated CO mass of 1.6 $M_\oplus$ but with a high inclination of 78°). Among the CO bearing debris disk population with an ideal inclination, HD138813 (inclination of 29° with a polar angle of 49.6°) is the one with the highest estimated CO mass, making it the best benchmark for our study.

Furthermore, in HD138813, the dust ring was observed to be ranging from 70 AU to 150 AU, which is smaller than the gas extent. This could be explained by the efficient viscous spreading of the gas as presented in Kral et al. (2016). If a planet is indeed embedded in the gas around HD138813, it would be more likely located at the edge of the dust belt: during the protoplanetary disk phase, the dust could have been accumulated at the edge of the planet gap where it could grow to planetesimal sizes. After the dispersal of the primordial gas, the collisions in the planetesimal belt would release dust and gas to the extent that we observe nowadays. In this scenario, as the planet is completely embedded in the gas, it would produce the strongest CO kinks (i.e., gas located closer to the planet will be more deviated from its keplerian rotation), making the detection easier.

2.2 Simulated observations of CO kinks in HD138813 to test their observability

In order to determine if CO kinks are observable in HD138813, we used different kind of simulations to produce synthetic ALMA images. Based on the characteristics of the gas presented earlier, we first run hydro-simulations with `FARGO2D1D`, with a Jupiter mass planet (arbitrary) located at the edge of the dust ring (i.e., at 70 AU). In this simulation, the gas is estimated to be only CO gas and its viscosity is intermediate (the turbulent viscosity parameter α is set to 10^{-3}). After integrating for $\sim 10^5$ years, the perturbed gas distribution is used as an input in a radiative transfer model called `RADMC3D`. Using the `simobserve` and `tclean` routines from `CASA`, we can therefore estimate under which ALMA configuration the CO kinks are observable.

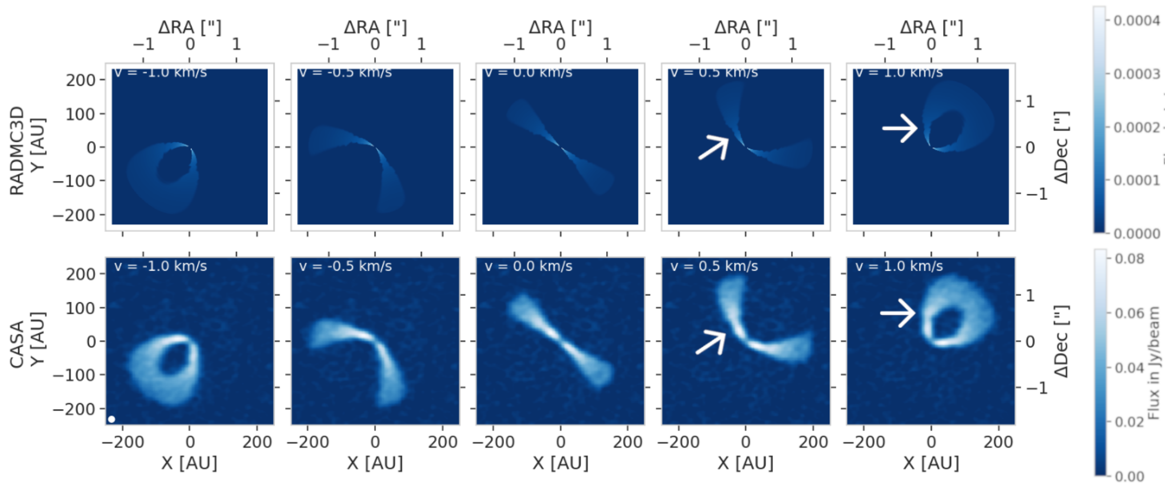

Fig. 2. *Top row: RADMC3D model of channels maps. The deviation from the center of the line is given in the top left corner of each plot. The CO kinks are marked by a white arrow. Bottom row: corresponding CASA simulated observation. In this case, the shown images are a combination of the C6 and C3 observations, the beam size is shown in the lower left corner of the first panel. The total integrated flux is 1.528 Jy.km/s, similar to the previous observations by Lieman-Sifry et al. 2016 (1.4 Jy.km/s).*

In Fig. 2, we show 5 channel maps of the CO(J=2-1) emission in our perturbed disk (the deviation from the center of the line is written in the top left corner of each map). The top row shows the total flux image coming from `RADMC3D` and the bottom row shows the corresponding image simulated in `CASA`. In the top row, we see that the typical size of the rotational velocity deviation is around 0.15" - 0.2", requiring a minimal resolution of 0.13" to be resolved. The C6 configuration allows for such observations at a reasonable integration time. However, with the combined observations in the C6 and C3 configurations, after 4h of integration in C6 and 1.36h in C3, we clearly start to distinguish the CO kinks.

3 Conclusions

As mentioned earlier, it is only since recently that gas has been discovered in debris disks. Observations as simulated here for HD138813 can help us better understand what kind of interactions the already formed planets might have with this old gas. The constraints derived from such future observations will help us improve our models for the description and evolution of this gas, which is fundamental to determine its origin. Furthermore, we are currently extending our study of HD138813 to different characteristics of debris disks in order to determine a more global observability study.

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