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The search for gas in debris disks: ALMA detection of CO gas in HD 36546.

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Abstract

Debris discs represent the last stages of planet formation and as such are expected to be depleted of primordial gas. Nonetheless, in the last few years the presence of cold gas has been reported in ~ 20 debris discs from far-IR to (sub-)mm observations and hot gas has been observed in the optical spectra of debris discs for decades. While the origin of this gas is still uncertain, most evidences point towards a secondary origin, as a result of collisions and evaporation of small bodies in the disc. In this paper, we present ALMA observations aimed at the detection of CO gas in a sample of 8 debris discs with optical gas detections. We report the detection of CO (^{12}CO and ^{13}CO) gas in HD 36546, the brightest and youngest disc in our sample, and provide upper limits to the presence of gas in the remaining seven discs.

1 Introduction

As exoplanetary studies progress, with more than 5000 planets confirmed, we tend to imagine planetary systems as simple associations of a central body (or more than one in some cases), i.e. a star, and a few to several planet sized objects revolving around it, much like our own Solar System. In doing so, we usually forget the plethora of other bodies that are present: moons, asteroids, comets, etc.; as well as the non-negligible amounts of dust and gas that are released via interactions of those components, mostly through collisions and evaporation.

However, minor bodies play a key role in the chemical and dynamical evolution of planetary systems, as they interact with each other and the proto-planets being formed. The Earth itself is thought to have been heavily impacted by small bodies in the system during the moon formation process and during the Late Heavy Bombardment event, possibly having its early atmosphere altered by volatiles (i.e., water) deposited by comets and asteroids. The study of the gaseous component of planetary systems in debris disks can help us investigate these kind of interactions, and have a significant impact in the study of habitability.

2 Circumstellar gas in debris disks

Gas has been classically expected to be depleted after the protoplanetary phase, and therefore not detectable around stars that have reached the main sequence already (i.e., debris disks). In the past 5-10 years, the increasing sensitivity of interferomertic facilities, such as ALMA, have led to multiple detections of CO gas in debris disks, challenging the classic view, and raising the question about why this gas is present in debris disks. While the community still investigates the possibility of this gas being a remnant of the protoplanetary phase, the general agreement is that secondary processes, such as evaporation and collisions of minor bodies, are acting as replenishment mechanisms of both the gas and dust components [9, 6].

The gas we find in debris disks can be separated in two populations. As mentioned above, (sub-)mm interferometric facilities have revealed the presence of CO emission in over 20 debris disks so far. This gas is usually located in the outer regions of the systems (¿10 au and up to several hundreds) and it has very low temperatures (a few Kelvin). Using optical spectroscopy, we can detect the gas located in the inner regions, at very high temperatures (over 1000 K) and most likely released by exocomets as they sublimate at very small distances from the star. This gas is mostly from highly refractory elements (e.g. Ca II) but has also been detected in multiple species in the ultraviolet region [15].

In both cases, the most likely origin of the gas is collisions or evaporation of minor bodies in the system, i.e. exocomets. The first detection of exocomets is reported in 1987 [4], where they observe variable absorption features overimposed to the Ca II line at 3933.66 Å. These absorptions were suggested to be originated by *Falling Evaporating Bodies* or FEBs, and later explained as bodies similar to the comets from the solar system [1].

3 Co-existence of hot and cold gas

In order to determine if cold and hot gas are co-existing and possibly connected to the presence of exocomets, I led a study presented in [12] that investigated the presence of absorption gas in systems with emission gas detection. At the time of the study, cold emission gas had been detected in 17 debris disks, out of which we selected 15 (excluding β Pic and Fomalhaut, due to their spectra being analyzed in previous research work). For those 15 sources, we obtained high resolution spectra containing the Ca II doublet. We collected inclinations for all the sources, with only one being unresolved. We separated the spectra between those with a non-photospheric absorption (i.e. a narrow absorption that is not originated in the stellar photosphere) and those without non-photospheric absorptions in the Ca II K line. After investigating if the origin of the absorptions is either from the circumstellar or interstellar environment by checking the radial velocities and the neighboring stars, we found out that ~90% of the debris disks with edge on orientations (¿ 70°) showed a circumstellar absorption, and similarly ~90% of the debris disks with face on orientations (¡ 70°) did not show any circumstellar absorption [1]. This is explained simply by a geometrical effect, meaning that the inner gas detected in absorption needs to transit the star in order to be detectable. The fact that cold and hot gas are simultaneously present in the majority of systems where both are detectable seems to be proof that they co-exist in debris disks, and they might have a common origin.

4 Results from ALMA observations

Given the presence of hot and cold gas seems to be simultaneous in debris disks, we designed the reverse experiment, where we selected a sample of stars with narrow circumstellar absorptions in the Ca II K line and searched for the cold gas counterpart [14].

We performed ALMA Band 6 (1.3 mm) observations in a sample of 8 debris disks with infrared luminosities between 10^{-5} and 10^{-3} and ages between 3 and 890 Myr.

We report detections in the dust continuum for 3 sources (HD 36546, HD 110411 and HD 158352) and ^{12}CO and ^{13}CO detections around HD 36546. We also report the detection of background sources in the field of view of HD 37306 and HD 182919. Detections around HD 36546 are shown in the top panel of Fig. 1, and the values for the fluxes, along with the rest of the detections can be found in [14].

The continuum detections allow to constrain the disk masses by assuming optically thin disks and a temperature of the dust consistent with the black body temperature of the thermal excess. The dust mass estimates of HD 36546 and HD 158352 are consistent with other debris disks, while the dust mass of HD 110411 appears to be particularly low, with less than 10^{-3} $M_{\oplus}$. CO gas mass was also estimated for HD 36546 using the optically thin ^{13}CO transition, yielding a gas mass of $(3.2 \pm 1.2) \times 10^{-3}$ M $\oplus$.

The line profile of the detected ^{12}CO line shows an asymmetric profile, with a larger flux in the blue-shifted velocities. Although the signal to noise is not enough to confidently measure any asymmetry in the ^{13}CO, a similar feature is observed (see bottom pannels of Fig. 1). This could indicate a significant asymmetry in the disk caused by disk perturbations from internal (self-stirring, planets) or external (binary, flybys) agents.

[1] β Pic and Fomalhaut were not included in this study, but also follow this trend.

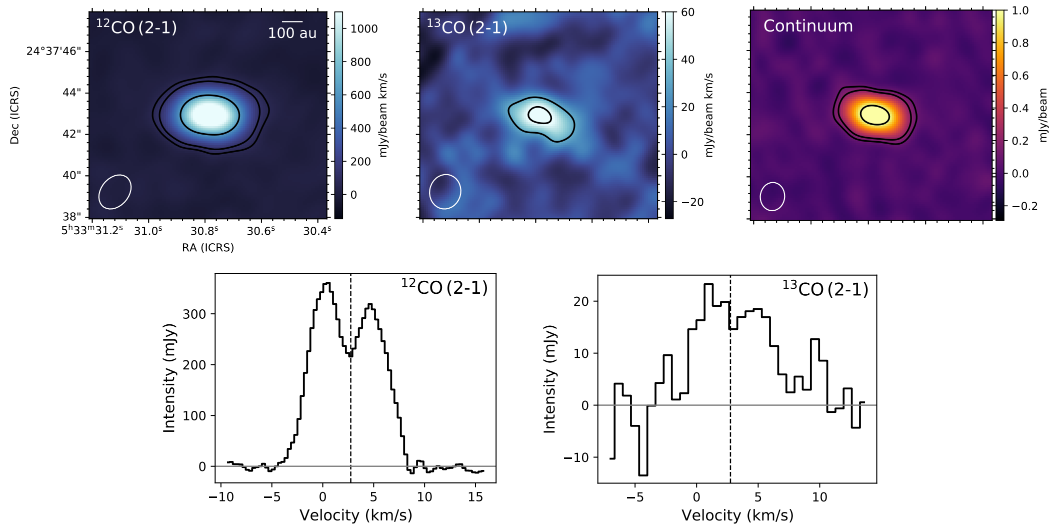

Figure 1: Figure from [14]. Emission observed in HD 36546. Top panels, left to right: Integrated emission of ^{12}CO (230.538 GHz), ^{13}CO (220.398 GHz) and continuum (1.33 mm). In all panels the size of the beam is indicated in the lower left corner. Contours indicate 5, 10 and 50 σ. Bottom panel, left to right: Spectra of ^{12}CO and ^{13}CO. The ^{12}CO panel shows the double peaked profile, characteristic of Keplerian rotation, and less visible in the ^{13}CO panel. The continuous horizontal line marks the continuum (at 0 mJy) and the vertical dashed line shows the systemic velocity of the disc.

4.1 HD 36546

The detection of large amounts of CO around HD 36546 fits in the overall picture we have of this system based on previous work.

Spectroscopic work by [8] showed a prominent feature at 8-9 μm, indicative of an over-abundance of carbon that could be due to a large collision of rocky bodies. [2] presented scattered light observations later re-analyzed in [7] where they reported the first estimation of the morphology of the disk (consistent with our findings in ALMA). They also included planet detection limits based on an estimated age of 3-10 Myr, with upper limits of 5-6 M_J at 23 au, and $\sim$ 2.5 M_J at larger separations. This system also has exocometary activity reported in [13], and a significant amount of Ca gas in the inner region of the system.

All these findings put together seem to indicate considerable dynamical activity in the system, and likely the presence of large bodies; i.e., planets.

4.2 The general picture

The detection of CO around HD 36546 puts this disk in context with previous detections, and shows a similar behaviour as other CO rich debris disks, with a high infrared luminosity and dust mass.

The overall result of the observations yielded a 12% of gas detections with only one out of 8 in the total sample. This appears to show that these systems lack a cold gas component, and therefore the rejection of the hypothesis of co-existence of hot and cold gas in them. However, theoretical predictions for gas production in debris disks depend on the amount of small bodies and dust particles in the system. [5] presented a model that predicted the CO mass in debris disks based on their infrared luminosity. Looking at Fig. 2, all our non detection have much lower dust masses than the disks with CO detections. It is thus possible that the low number of cold gas detections is instead due to insufficient sensitivity of our observations, rather than the lack of cold gas in these systems.

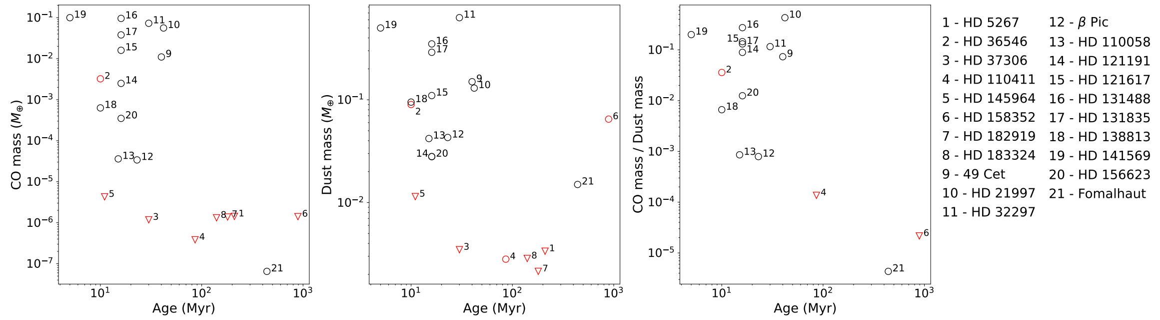

Figure 2: Figure from [14]. Context of the sample compared to other debris discs around A-type stars with detected CO gas. Red symbols mark the positions of the stars in the sample, numbered from 1 to 8. Triangles indicate upper-limits for non-detections. Black circles mark other debris discs with detections in the literature numbered from 9 to 21 [10, 11, 3].

5 Summary

The work presented in this contribution summarized the ALMA observations of project 2019.1.01517.S (PI: I. Rebollido). We report the detection of ^{12}CO and ^{13}CO in the debris disk HD 36546, which confirms this is a complex and interesting system with cold gas [14], hot gas and exocomets[13] and a debris disk with several belts and a carbon enhancement [8]. We also report continuum detections for HD 158352 and HD 110411. The rest of the disks observed within the same ALMA program showed no gas or dust detections, which is probably linked to their low dust content as suggested by [5]. This analysis and results can be found in [14].

We intend to follow up with ALMA observations for the HD 36546 disk to improve the spatial resolution, and recent observations with JWST (GO 2053, PI: I. Rebollido) will allow to investigate the presence of volatiles in the warmer regions of the disk and delivery mechanisms.

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