Measuring gas distribution in gapped disks

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1 Background and Motivation

The discovery of small scale structures (< 30 au) in the distribution of gas and dust around protoplanetary disks has been a major achievement of ALMA early science observations. The main morphologies observed so far are rings (ALMA partnership 2015, Andrew et al. 2016, Dipierro et al. 2017, Fedele at al. 2017, 2018, Isella et al. 2016, Zhang et al. 2016), spirals (Pérez et al. 2016), and crescents (e.g., Van der Marel et al. 2015, Casassus et al. 2015, Boehler et al. 2017, 2018). The recently completed ALMA large program carried out by our group (2016.1.00484.L) has revealed that dust rings are common, if not ubiquitous, among protoplanetary disks. Indeed, 16 out of the 20 observed sources show one or more rings in the 1.3 mm dust continuum emission, while spirals and crescent are more rare and are observed in only 5 and 1 disks, respectively (Huang et al. in prep.).

Imaging ringed disks at multiple wavelengths in both the continuum and molecular line emission is key to investigate the nature of the observed structures. For example, observations of the HL Tau and HD 163296 systems in the continuum emission between 0.87 mm and 7 mm reveal that the grain size distribution varies with the orbital radius, and that grains larger than about 1 mm are concentrated at the location of the dust rings (Carrasco-Gonzalez et al. 2017, Isella et al. in prep). Moreover, observations of the ^{12}CO, ^{13}CO, and $C^{18}O$ line emission of HD 163296 reveal an increase of the dust-to-gas ratio at the position of the dusty rings (Isella et al. 2016, Liu et al. 2018). In practice, the dust rings in HL Tau and HD 163296 are regions were mm-size particles are concentrated both with respect of the circumstellar gas and of smaller particles. These results are in agreement with aerodynamic trapping of dust grains at the location of gas pressure maxima, and have strong implications for understanding the evolution of solids in protoplanetary disks and the formation of planetesimals. Dust traps can stop the inward migration of pebbles and provide a solution for the long standing "radial drift" problem (see the review by Testi et al. 2014). Furthermore, the concentration of solids within dust traps make them an ideal place for the formation of planetesimals (through, e.g., streaming instability, Youdin and Goodman, 2005). Finally, since the dust concentration depends on the gas density and turbulence (via the dust Stokes number), the comparison between models and observations provide indirect constraints on the total disk mass and its viscosity.

The fact that dust rings are very common in the observed disk population suggests that dust traps might indeed be the dominant process controlling the formation of planetesimals. But two main questions remain pending: are all the rings observed so far dust traps? And, what is their origin? **Here, we propose to address these questions by mapping the molecular line emission in two disks characterized by outstanding ring structures. The proposed observations will measure the radial profile of the gas-to-dust ratio and assess both the presence of dust traps and their origin.** Whereas the selected sample is too small to provide definitive answers, it will double the number of disks for which a similar investigation has been attempted, and would enable us to sharpen the observational setup and the analysis tools required to embark in a future larger observational proposal.

2 Immediate objective and feasibility

The immediate goal of this project is to map the protoplanetary disks around the young low-mass stars AS 209 and Elias 24 in both the ^{12}CO, ^{13}CO, and $C^{18}O$ (2-1) emission lines, and 1.3 mm dust continuum. Observations of ^{12}CO and dust continuum emission were already acquired as part of our large program (Figure 1), so in this proposal we focus on acquiring images in the ^{13}CO and C^{18}O (2-1) lines.

Besides HL Tau, TW Hya, and HD 163296, AS 209 and Elias 24 are in several respects the most outstanding ringed disked discovered so far, and the two best targets to measure the radial gas distribution. As shown in Figure 1, both disks show very sharp and center-symmetric rings in the 1.3 mm dust continuum emission. The sharpness of the rings is important to precisely locate their radii, while the lack of azimuthal asymmetries allows us to improve the signal-to-noise ratio of the line emission by averaging on elliptical rings (see lower panel of Figure 1). In the case of AS 209, the radial profile of the continuum emission shows several peaks and troughs. The two outermost troughs trace dust gaps that extend radially from about 55 au to 75 au, and from 85 au to 125 au, respectively. Elias 24 disk is instead characterized by a single dust gap extending from about 45 au to 70 au. The large radius and width of these gaps allows us to spatially resolve them across more than 2 resolution elements at the proposed resolution of 10 au.

Another important reason of choosing AS 209 and Elias 24 is that they were already imaged in the ^{12}CO (2-1) emission line at the same resolution requested in this proposal (ALMA large program, Figure 1). In the case of AS 209, the radial profile of the ^{12}CO emission does not show any sharp variation within the dust gaps despite a drop in the dust emission by almost a factor of 100. Similarly, the ^{12}CO emission decreases smoothly within the dust gap in Elias 24, though we detect a tantalizing peak in the line emission at the same radius of the bright dust ring ($\sim$75 au). As discussed in Isella et al. (2016), the ^{12}CO line emission becomes optically thick at very low column densities and it is therefore a good tracer of the gas temperature but a lousy tracer of the gas density (the gas temperature estimated from the ^{12}CO line is important to asses the feasibility of the proposed observations and is discussed in the Technical Justification). The smooth profile of the ^{12}CO emission across the dust gaps indicates the lack of steep radial temperature variations and implies gas densities larger than about 10^{-2} g cm^{-2} (this is the surface density corresponding to $\tau_{12CO(2-1)} \sim 1$ assuming a cosmic abundance of 10^{-4}, a gas temperature of 50 K, and a line width of 1 km s^{-1}). On the other hand, the dust emission (or lack of dust emission) measured within the dust gaps implies gas column density lower than 10^{-1} g cm^{-2} (assuming a dust opacity of 2.3 cm^2 g^{-1}, a dust-to-gas ratio of 0.01, and the same temperature of 50 K). The lower and upper limits on the gas surface density set by the ^{12}CO and continuum observations, respectively, are compatible with both an equal drop in gas and dust density across the dust gaps (and therefore a constant gas-to-dust ratio), and with a shallower drop (or no drop at all) in the gas density (and consequently a variable gas-to-dust ratio). By probing gas column densities up to 500 times higher than that traced by ^{12}CO, the proposed observations of the ^{13}CO and C^{18}O (2-1) lines will instead place stringent constraints of the gas surface density and gas-to-dust ratio, enabling us to investigate whether the observed dust rings are dust traps.

Finally, we chose AS 209 and Elias 24 because the were already imaged in the ^{13}CO and C^{18}O (2-1) line emission, though at an angular resolution (0.3") insufficient to resolve the dust gaps (2015.1.00486.S, PI: D. Fedele; 2013.1.00498.S, PI: L. Pérez). These previous observations are important because they already provide the short spatial frequencies required to recover the large scale emission, and allow us to estimate the sensitivity required to image the same lines at high angular resolution (see the Technical Justification).

3 Data analysis and outcome of the project

The proposed ALMA observations will be processed as follow. First, we will check and improve, if necessary, the data calibration performed by the ALMA pipeline, and perform self-calibration on both the continuum and line data. The calibrated visibility data will then be compared to synthetic models of the disk emission to constrain both the disk 3-D temperature and density structure.

The data analysis will be performed in two steps. In the first phase, we will compare the observations to disk models that assume a parametric profile for the gas and dust surface density. This simplistic approach will allow us to efficiently explore a wide range of gas and dust surface density values and constrain the gas-to-dust ratio as a function of the orbital radius, and, in particular, across the dust gaps and rings. The parametric models will be based upon the ongoing analysis of the ALMA large program data shown in Figure 1 (Huang et al. in prep, Guzman et al. in prep), and will include 3D radiative transfer and ray tracing simulations of the dust and gas emission performed with RADMC3D (Dullemond et al. 20XX). The synthetic models will be Fourier transformed and sampled at the same uv-plane coordinates as the real observations to properly account for the shape of the synthesized beam and spatial filtering. The main outcome of this analysis will be a scientific paper discussing the radial profile of the gas and dust density, as well the gas-to-dust ratio, in AS 209 and Elias 24, and the implications in terms of the existence of dust traps in these disks.

The second step of analysis would consist in comparing the observations to models for the planet-disk interaction to constrain mass and orbital radius of the planets possibly responsible for the observed perturbations. The dusty rings observed in Elias 24 and AS 209 are indeed reminiscent of the expected perturbations induced by planets on the circumstellar material. The lack of azimuthal asymmetries implies that either such planets have masses lower than Jupiter, or that the disk viscosity is large enough to quench instabilities capable to generate asymmetric structures, such as, e.g., the Rossby-wave instability. Our group has been at the forehead of the interpretation of ALMA observations in the framework of planet-disk interaction models (Jin et al. 2016, Liu et al. 2018). The analysis will follow that discussed in Liu et al. (2018). TO BE COMPLETED

4 References

[] Dipierro et al., 2017, MNRAS, 475, 5296 [1] Fedele, D.; Tazzari, M.; Booth, R.; Testi, L.; Clarke, C. J.; Pascucci, I.; Kospal, A.; Semenov, D.; Bruderer, S.; Henning, Th.; Teague, R., 2018, A&A, 610, 9 [2] Fedele, D.; Carney, M.; Hogerheijde, M. R.; Walsh, C.; Miotello, A.; Klaassen, P.; Bruderer, S.; Henning, Th.; van Dishoeck, E. F., 2017, A&A, 600, 72

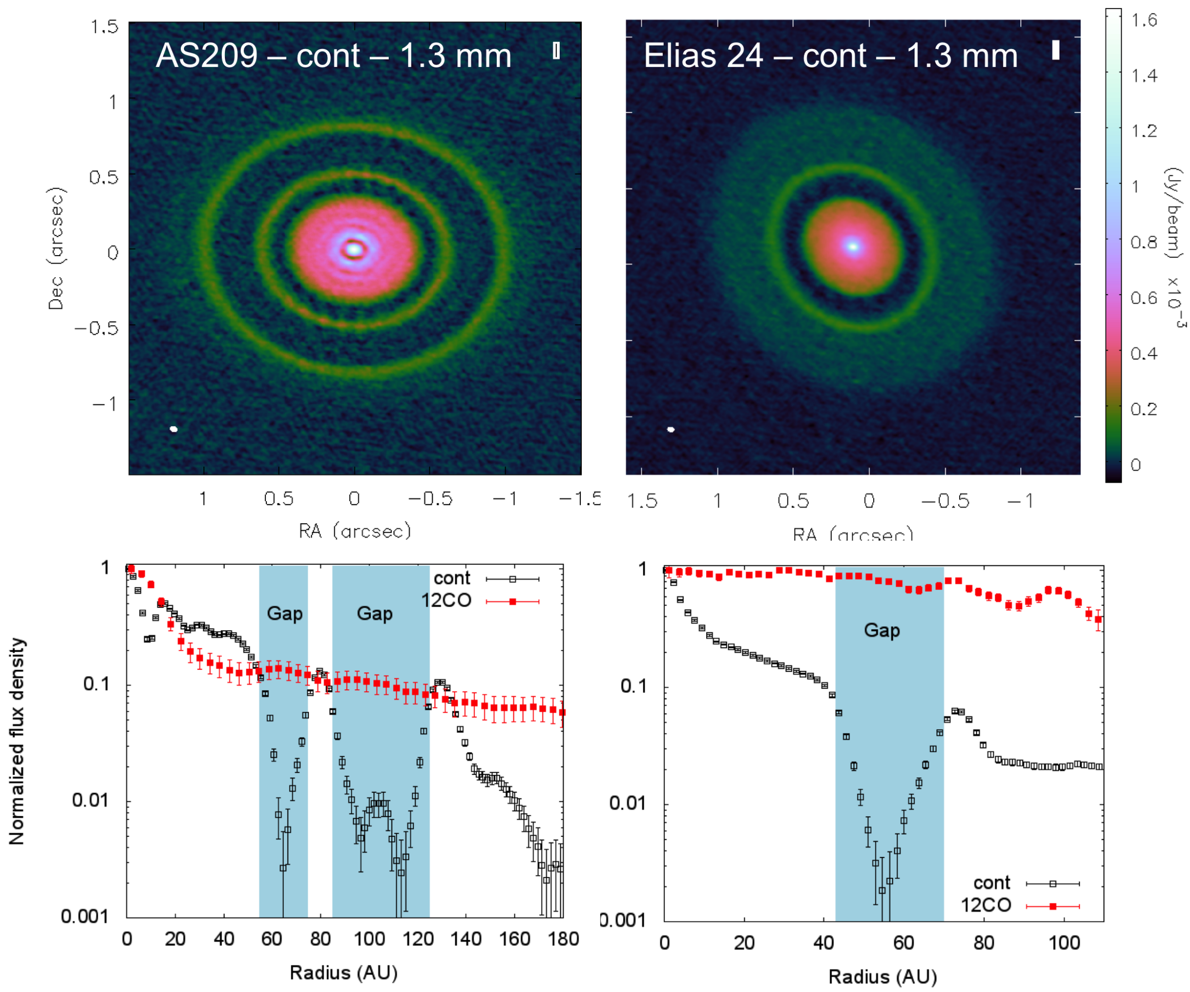

Figure 1: *(From the ALMA large program, Huang et al. in prep., Guzman et al. in prep.) Top: Images of AS 209 (left) and Elias 24 (right) in the 1.3 mm dust continuum emission. The angular resolution is 0.035", corresponding to a physical scale of about 5 au at the distance of 130 pc. Bottom: radial profile of the dust continuum and ^{12}CO (2-1) emission. The radial profile of the ^{12}CO emission was obtained by imaging the line emission at a resolution of 0.08". The symbols for the continuum and line emission are spaced by half resolution element. The location of the most prominent dust gaps is indicated with colors. In the case of AS 209, no decrement in the ^{12}CO intensity is observed across the gaps despite a drop of almost a factor of 100 in continuum emission. In the case of Elias 24, the ^{12}CO drops slightly within the dust gap and shows a tantalizing maximum at the same position of the dust ring at 75 au from the central star. In both cases the high optical depth of the ^{12}CO line does not allow to measure the gas density across the dust gaps.*