Investigating the Future Potential of an Upgraded ALMA to Image Planet-forming Disks at Sub-astronomical-unit Scales

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Abstract

In recent years, ALMA has been able to observe large-scale substructures within protoplanetary disks. Comparison with the predictions from models of planet–disk interactions has indicated that most of these disk substructures can be explained by the presence of planets with the mass of Neptune or larger at orbital radii of ≈5–100 au. Better resolution is needed to observe structures closer to the star, where terrestrial planets are expected to form, as well as structures opened by planets with masses lower than Neptune. We investigate the capabilities of a possible extension to ALMA that would double the longest baseline lengths in the array to detect and resolve disk substructures opened by Earth-mass and super-Earth planets at orbital radii of 1–5 au. By simulating observations of a family of disk models using this extended configuration in ALMA Bands 6 and 7, we show that an upgraded ALMA would detect gaps in disks formed by super-Earths as close as 1 au, as well as Earth-mass planets down to 2–3 au from the young host stars in nearby star-forming regions.

Unified Astronomy Thesaurus concepts: Protoplanetary disks (1300)

1. Introduction

Planets form out of the gas and dust contained in disks orbiting young pre-main-sequence stars (see Andrews 2020 for a recent review). Besides providing the raw material for the development of planetary cores and atmospheres, these circumstellar disks also play a key role in the dynamics of the newly born planetary systems. This is because the physical interaction between the disk and planets naturally leads to an exchange of angular momentum, with significant consequences for both planets and the disk within the same system (Kley & Nelson 2012).

The main effect of the change in the planet angular momentum is an evolution of the planet orbit, a process known as planet migration (Goldreich & Tremaine 1980; Lin & Papaloizou 1986). In turn, the change in the angular momentum of the disk can lead to significant perturbations in the disk’s physical evolution. The morphology and physical characteristics of these perturbations, or substructures, can strongly modify the subsequent evolution of the system both by triggering or inhibiting the formation of a new generation of planets and by altering the disk–planet interaction (Baruteau et al. 2014).

Observationally, the direct detection and characterization of these disk substructures therefore have two main purposes. The first is that they allow us to test the predictions of physical models of disk–planet interaction (e.g., Dong et al. 2015a, 2015b). If the properties of a companion in a real system are known, a detailed comparison between observations and theoretical models can help us to refine our theoretical models. Moreover, the detection of disk substructures can be used as a way to unveil the presence of young planets in these systems. Although this is an indirect method for the detection of exoplanets, in some systems this may provide the only viable method to detect exoplanets, especially those that are highly embedded within the disk (Sanchis et al. 2020). The detailed physical modeling of the observed substructures can then be used to extract estimates for some of the main planetary parameters, such as planet mass and orbital radius (e.g., Jin et al. 2016; Dipierro et al. 2018), after accounting for the known degeneracies between the properties of the disk substructures, planet mass, gas viscosity, and disk aspect ratio (e.g., Fung et al. 2014).

One of the most spectacular successes of the Atacama Large Millimeter/submillimeter Array (ALMA) has been the imaging at (sub)millimeter wavelengths of several substructures in the dust continuum emission from disks located in nearby star-forming regions (distances <200 pc). The results of the first ALMA surveys with angular resolution lower than about 0′1, corresponding to spatial resolutions <15–20 au, indicate that disk substructures are nearly ubiquitous in mapped systems (Andrews et al. 2018; Cieza et al. 2021), with the majority of them showing nearly concentric annular rings and gaps (Huang et al. 2018).

In several cases, the morphology of these features is in line with the predictions from models of disk–planet interaction, and estimates for the planet masses and orbital radii have been extracted from the comparison between the substructures predicted from the models and those observed with ALMA. For example, Zhang et al. (2018) have used the results of global 2D hydrodynamical simulations with gas and dust coupled to a radiative transfer code to obtain synthetic images for the dust continuum emission at the wavelengths of the Disk Substructures at High Angular Resolution Project (DSHARP) ALMA Large Program. From a close comparison with the annular substructures observed in several of the DSHARP targets, they inferred relatively large planet masses ranging between the mass of Neptune up to ~10 MJup and orbital radii between about 10 and 100 au. Similar ranges for these planetary properties were obtained by Lodato et al. (2019), who combined the DSHARP sample with those from other ALMA observations of nearby disks at similar wavelengths (Long et al. 2018).
As highlighted in these studies, the lack of planets with mass below Neptune and with orbital radii $<10$ au, more in line with the exoplanets typically observed around main-sequence stars, is almost certainly due to the limited angular resolution of the ALMA interferometer. The width of a gap opened by a planet in the disk gets smaller for planets with lower mass and orbiting closer to the star (Kley & Nelson 2012). Hence, the only way to alleviate the observational limitations and probe disk substructures due to terrestrial planets is by observing disks with better resolution than is possible with the current ALMA interferometer.

Recently, Ricci et al. (2018) and Harter et al. (2020) presented investigations on the potential of a future next-generation Very Large Array to detect the signatures of young planets in the dust continuum emission of disks at wavelengths of $3 \text{ mm}$ and longer. A similar investigation has been presented by Ilee et al. (2020) on predictions of future radio observations with the Square Kilometre Array. In this work we present the potential of a possible future extension of the current ALMA array to detect and spatially resolve disk substructures due to Earth-mass and super-Earth planets at orbital radii lower than $10$ au, i.e., in the disk regions where terrestrial planets are expected to form. The extension to the ALMA array considered here was inspired by the investigations discussed in the ALMA Development Program: Roadmap to 2030 (Carpenter et al. 2020) and consists of an array configuration with longest baselines of about $32$ km, a factor of 2 longer than the current ALMA longest baselines.

Section 2 describes the methods used for our investigation, and Section 3 presents the main results obtained in this work. After a discussion in Section 4, the main conclusions are summarized in Section 5.

2. Methods

In this section we describe the methods used for our investigation. These comprise global 2D hydrodynamic simulations that calculate the disk–planet interaction in a disk made of gas and dust particles, the derivation of synthetic images for the dust continuum emission from these models, and finally, the simulation of observations with the current ALMA as well as with an extended ALMA with longer baselines.

2.1. Hydrodynamic Simulations for the Disk–Planet Interaction

The methods used for the hydrodynamic simulations that calculate the time evolution of a disk made of gas and dust particles gravitationally interacting with a planet are the same as in Zhang et al. (2018) and Harter et al. (2020), which are based on the Dusty FARGO-ADSG code (Masset 2000; Baruteau & Masset 2008a, 2008b; Baruteau & Zhu 2016).

We follow the same parameterization scheme as in Harter et al. (2020), with a disk with an initial gas surface density $\Sigma_g = \Sigma_{g,0}(r/a_p)^{-1}$, with $r$ being the stellocentric radius, $a_p$ the planet orbital radius, and $\Sigma_{g,0}$ a normalization factor. At the beginning of the simulations the disk is azimuthally symmetric, this symmetry is broken early on because of the interaction with the planet. Because our main goal is to test the potential of an extended ALMA to detect disk substructures due to planets in the terrestrial planet-forming regions of disks, in our simulations we considered planet orbital radii $a_p = 1, 2, 3, \text{ and } 5 \text{ au}$. Our numerical grid is made of $750$ grid points in the radial direction spanning the interval $[0.1 a_p, 10 a_p]$ and $1024$ grid points covering the full azimuthal direction $[0, 2\pi]$. In order to explore the dependence of the results of our investigation on the disk surface density (hence, disk mass), we ran simulations with $\Sigma_{g,0}$ values of $100, 300, 600, 1200$, and $2400 \text{ g cm}^{-2}$. The initial dust surface density is $1/100$ of the initial gas surface density, and our simulations account for a power-law grain-size distribution with a power-law exponent equal to $-3.5$ (see, e.g., Ricci et al. 2010) and truncated at a maximum grain size of $1 \text{ cm}$ (see Zhang et al. 2018; Harter et al. 2020).

The models assume a local isothermal equation of state with temperature $T$ related to the pressure scale height $h$ via the relation for vertical hydrostatic equilibrium: $h/r = c_s/\sqrt{g}$, where $c_s$ is the local sound speed $c_s = \sqrt{RT}/\mu$, with an assumed mean molecular weight of the gas $\mu = 2.35$, and $\sqrt{g}$ is the local Keplarian velocity. As in Harter et al. (2020), our simulations assume a value of $0.03$ for the vertical aspect ratio $h/r$ at the radial location of the planet, and a constant value of $10^{-5}$ for the Shakura–Sunyaev $\alpha$ parameter for the gas viscosity across the disk (Shakura & Sunyaev 1973). Our model considers a passive disk, in which the temperature is determined by the stellar luminosity $L_*$ and disk-flaring factor $\phi$ via $T(r) = (\phi L_*/8\pi\sigma)^{1/4}$, where $\sigma$ is the Stefan–Boltzmann constant. Our models were calculated with $L_* = 10 L_\odot$ and $\phi = 0.02$ (D’Alessio et al. 2001). Any contribution to the disk temperature by internal viscous heating was ignored.

In these models, the planet and stellar mass, $M_p$ and $M_*$, respectively, enter via the ratio $q = M_p/M_*$, and for this work, we launched simulations with two different $q$ values of $1$ and $10 M_\oplus/M_*$, representing planets with the mass of Earth and of a super-Earth around a solar-mass star, respectively. Our simulations were run for $7000$ and $5000$ planetary orbits for $q = 1$ and $10 M_\oplus/M_*$, respectively.

The results of these simulations were used to produce synthetic maps for the dust thermal continuum emission at two wavelengths, $0.88$ and $1.25 \text{ mm}$, corresponding to ALMA Bands 7 and 6, respectively, following the method detailed in Zhang et al. (2018). These wavelengths were chosen as these spectral bands provide the best sensitivity to thermal emission from dust with ALMA. To derive these maps, we assumed a distance to the disk model of $140 \text{ pc}$, similar to the distance to nearby star-forming regions, which are routinely observed with ALMA.

2.2. Simulated ALMA Observations

The synthetic maps described in the previous section for the dust continuum emission derived from our models were used to predict the results of future observations with ALMA. This was done using version 5.7 of the CASA software package (McMullin et al. 2007).

For these calculations, we considered two main array configurations. To simulate observations with the longest baselines in the current ALMA array, we considered the array configuration file alma.cycle6.10.cfg available in CASA, with baselines ranging from $256 \text{ m}$ to $16.2 \text{ km}$.

To simulate observations with a plausible future extension to the current ALMA array, we produced a new configuration, called here $ax54$, which merges $42$ existing antenna pads.

\footnote{Our models do not account for planet migration.}
(orange dots in Figure 1), as well as 12 possible new pads located within the ALMA concession and the Atacama Astronomical Park that are being considered for additional baselines (blue dots; see Figure 9 in the ALMA Development Program: Roadmap to 2030, Carpenter et al. 2020). All antennas have a diameter of 12 m. Baseline lengths in this configuration range from 44 m to 32.6 km. We simulated aperture synthesis interferometric observations with an on-source time of 8 hr for both the ax54 and cycle6.10 configurations. The uv coverage obtained with these observations is shown in Figure 2.

We complemented the observations with the two previous array configurations with a relatively short, 1 hr integration on a more compact configuration, namely alma.cycle6.4, with baselines ranging from 15 to 783 m, with the goal of minimizing the interferometric filtering out of the most extended scales of the disk emission. Tables 1 and 2 quantify the amount of flux loss due to interferometric filtering at 0.88 mm and 1.25 mm, respectively, with the alma.cycle6.10 and ax54 configurations, without the addition of alma.cycle6.4. With the addition of this more compact configuration, the amount of interferometric flux loss was typically reduced by a factor of ≈2.

Simulated measurements of the interferometric visibilities were carried out using the simobserve task in CASA. We considered a total bandwidth of 7.5 GHz in a single spectral window (in the Appendix, we also investigate the effects of considering the spatial variation of the disk emission across four spectral windows, as in real ALMA observations, but we found only very modest differences in the final image). The simulated atmospheric noise parameters we used correspond to an adopted value for the precipitable water vapor (PWV) of 0.5 mm. The ground temperature was set to 269 K.

The tclean task in CASA was used to image the interferometric visibilities. We adopted a Briggs weighting scheme and after testing the imaging with different robust parameters $R$, we found that $R = -1$ provided the best results in terms of maximizing the signal-to-noise ratio (S/N) of the disk substructures. We also used a multiscale deconvolver (as in Cornwell 2008) with scales of 0, 7, and 30 pixels. Because as described in Section 2.1, the radial domain of our simulations depends on the planet orbital radius $a_p$ but the number of pixels in the maps is the same for all our models, then the pixel size in our maps scales linearly with $a_p$ as pixel size [µas] = 71.4 $a_p$/au.

Table 3 lists the sizes of the synthesized beams obtained with an 8 hr aperture synthesis with the ax54 configuration at 0.88 mm and at different source declinations. The chosen values are close to the mean declinations of young stars in nearby star-forming regions, which are natural targets for studies of protoplanetary disks at high spatial resolution. Within the sample of regions considered here, which span declinations from $-77\degree$ to $+24\degree$, the beam major and minor axes range between 5.9–8.3 mas (0.9–1.2 au) and 4.0–4.5 (0.6–0.7 au) mas, respectively. The maps presented in this paper were derived assuming a decl. of $-35\degree$.

We also compared the results of the traditional CLEAN deconvolution algorithm (tclean task in CASA) to those produced by the frankenstein package described in Jennings et al. (2020). The frankenstein algorithm fits the real visibilities as a function of baseline distance with a nonparametric Gaussian process. In the case of an azimuthally symmetric source, this function is related to the radial profile of the source. Consequently, this fit is able to reconstruct radial profiles directly from the visibilities rather than producing them from a 2D image. This avoids the loss of resolution, especially with long baselines, from using the CLEAN algorithm to subtract the side lobes from the dirty image. However, since frankenstein makes the assumption of an azimuthally symmetric disk, it is not valid for disks with significant azimuthal asymmetry such as arcs or spirals. Most, but not all, of our models only feature annular gaps, lacking significant azimuthal dependence in their substructures. In those cases, frankenstein is capable of retrieving information on their disk structure at subbeam resolution. Although all of the maps presented here were obtained using tclean, in Section 3 we also show the comparison between the results with tclean and frankenstein obtained for one specific disk model without significant azimuthal asymmetries.

3. Results

We will begin our discussion of the results by examining the case of the disk model with $\Sigma_{0,0} = 300$ g cm$^{-2}$, and a planet with $q = 10 M_\oplus/M_\odot$ at an orbital radius of 3 au. Figure 3 displays the radial profiles for the gas and dust surface densities of this disk model, after azimuthal averaging. The planet opens a pronounced gap in the gas around its orbital radius bracketed by two prominent density bumps but also less pronounced local density minima and maxima farther from the planet. The local
density maxima correspond to local pressure maxima, which are effective at slowing down the radial migration of grains and trapping the dust at those locations (Pinilla et al. 2012). As a consequence, the spatial distribution of dust density presents clear rings interleaved by regions of depleted dust (gaps).

The dust continuum map extracted for this model at 0.88 mm, shown on the left panel in Figure 4, exhibits the primary gap at 3.0 au, corresponding to the orbital location of the planet, flanked by the two secondary gaps at 2.3 and 3.9 au. No other gaps are visible because the emission from dust...
within the other less depleted gaps is optically thick. The central panel in the same figure shows the results of our ALMA simulations with 8 hr of integration time in the cycle6.10 array configuration. The main gap produced by the planet is barely visible on the map, and at the resolution of these observations the gap is unresolved (beam size ≈ 3 × gap radial width). As a consequence, although the current ALMA array would detect this gap, no information on the planet’s properties could be extracted from the radial width and depth of the gap.

The results displayed in the right panel show that the extended ALMA array is capable of spatially resolving the main gap and also detecting the outer secondary gap at 3.9 au from the star. Because of the elongation of the synthesized beam, close to the north–south direction, this secondary gap is more clearly visible, although not spatially resolved, toward the east and west sides of the disk.

Figure 5 shows the dust continuum maps for the models with the same $q$ and $a_p$ values as in Figure 4 but with different $\Sigma_{q,0}^g$. The variation of this parameter has two main effects on the disk and its emission. Because the initial dust-to-gas ratio in our simulations is fixed, varying the gas densities leads to a change in the dust densities as well, with a consequent variation of the dust thermal emission. The fact that the surface brightness is relatively similar for the models presented in Figure 5 is due to the relatively high optical depth of the dust emission at 0.88 mm in the disk regions shown even for the models with lower $\Sigma_{q,0}^g$.

The other main effect, which has a more significant impact on the maps derived from our models, is due to the dependence of the dynamics of dust on the local gas surface density. The Stokes parameter quantifies the aerodynamic coupling of dust with gas, and a variation of this parameter can have a strong effect on the dynamics of the grains embedded in the disk. In particular, at a given grain size of the dust, which is fixed in our simulations, the Stokes parameter $St \propto 1/\Sigma_{q,0}^g$. Hence, the dust in disks with higher $\Sigma_{q,0}^g$ has lower St values. Because in all our models $St < 1$, this means that the dust in the denser disks is more dynamically coupled to the gas, hence the dust density and emission will appear radially smoother and more axisymmetric than in disks with lower densities.

In fact, the only model showing clear azimuthally asymmetric substructures in Figure 5 is the one with the lowest gas density ($\Sigma_{q,0}^g = 100 \text{ g cm}^{-2}$, top row), where the most prominent features are arcs instead of full rings as in the other models. The bright east side of the most prominent arc is detected with the extended ALMA, whereas the same feature appears to be blended with nearby dust emission in the current ALMA map, in which the only visible substructure is a wide asymmetric gap. The other rows in Figure 5 show that the extended ALMA can detect the primary gap in the disks with $\Sigma_{q,0}^g$ values up to $\approx 1200 \text{ g cm}^{-2}$, while the gap is too narrow and with too little contrast to be detected in denser disks.

Figure 6 displays the results for models with varying orbital radii of the planet, ranging from $a_p = 1$ au (top row) to 5 au (bottom row). The initial gas surface density at the planet orbital radius $\Sigma_{q,0}^g$ was set to $100 \text{ g cm}^{-2}$ to maximize the number of disk substructures. For the model with $a_p = 5$ au, the extended ALMA detects and resolves multiple rings and asymmetric arcs, which the current ALMA does not resolve. The extended ALMA detects the gap also for the case of $a_p = 1$ au, even though the individual substructures are unresolved.

In Figure 7 we present the models with $q = 1 M_\odot/M_\odot$, $\Sigma_{q,0}^g = 100 \text{ g cm}^{-2}$ and for varying $a_p$. Compared with the maps shown previously, the predicted gaps are significantly shallower because of the lower gap radial width and depth expected for a lower-mass planet. In our calculations, the gaps are not clearly detected with either the current or the extended ALMA, even though some level of depression in the surface brightness for the $a_p = 5$ au model is seen at low $S/N$ with the ax54 configuration.

When no significant azimuthal asymmetric features are present, frankenstein can be used to enhance the $S/N$ of the annular rings and gaps that are otherwise not visible in the images obtained with deconvolution via CLEAN. To demonstrate this, the left panel in Figure 8 shows the radial profile of the azimuthally averaged surface brightness produced by the
Figure 5. Same as in Figure 4 but with models with different $\Sigma_0$ values as indicated on the left panel of each row. For all of the models presented here, $q = 10 M_\odot/M_\oplus$ and $a_p = 3$ au.
CLEAN algorithm for a model with $\Sigma_{g,0} = 100 \, \text{g cm}^{-2}$ and $q = 10 \, M_\oplus/M_\ast$. No gap can be seen with either the current or extended configuration. The right panel in the same figure shows the radial profiles obtained with \texttt{frankenstein}. Although the uncertainties inferred by the \texttt{frankenstein} code are somewhat underestimated—a
limitation described by Jennings et al. (2020)—a gap is visually evident when analyzing the data from the extended configuration with *frankenstein*, which would otherwise be invisible using *CLEAN*.

All the maps discussed so far were derived at a wavelength of 0.88 mm. This wavelength is within the spectral coverage of ALMA Band 7, which for typical spectral energy distributions of T Tauri stars provides the best sensitivity to the emission from dust in protoplanetary disks. Figure 9 shows the dust continuum emission maps for models with varying $\Sigma_{g,0}$ values as in Figure 4 but for a wavelength of 1.25 mm, which falls within the spectral coverage of ALMA Band 6. One benefit of observing disks at longer wavelengths is that their dust emission is more optically thin. Although with a lower $S/N$ than in Band 7, this figure shows that the gaps can be detected with the extended ALMA array also in Band 6, with a significant improvement over the similar observations with the cycle6.10 configuration. In the Appendix, we show the expected improvements on the imaging of young disks when considering the capabilities of the new ALMA Band 6 receivers, which are currently under development.

4. Discussion

The results presented in the previous section show the potential of an upgraded ALMA with baselines longer by a factor of 2 over the current ALMA capabilities to detect disk substructures due to planets at orbital radii of 5 au and lower in nearby star-forming regions. For low values of the gas viscosity in these disk regions ($\alpha = 10^{-5}$), our simulations indicate that planets with $q = 1$ and $10 \, M_{\oplus}/M_\star$ are massive enough to open gaps that can be observed in the dust continuum emission with an upgraded ALMA. We note here that for disks with higher...
gas viscosity, planets with higher masses than those investigated here would be needed to open gaps in the disk. Although this is an indirect method to probe planets embedded in the parental disk, it may be the best method, if not the only one, for several systems because of the expected high extinction of the planet light at optical/infrared wavelengths due to dust in the disk (Sanchis et al. 2020; Asensio-Torres et al. 2021).

The detection of young planets in these inner regions of protoplanetary disks would complement the results obtained so far with ALMA in the disk outer regions, i.e., at stellocentric radii larger than about 10 au (see, for example, the results of the DSHARP Large Program; Andrews et al. 2018; Zhang et al. 2018). This would open the investigation to a more complete comparison between the properties of the detected exoplanet population and those of the young planets still embedded in the disk, which would shed light on the history of formation and migration of the known exoplanets (e.g., Zhang et al. 2018; Lodato et al. 2019; Kanagawa et al. 2021). In particular, the planets considered in this work are the likely precursors of the ice giant planets found at a few astronomical units from their star, which Suzuki et al. (2016) claimed to be the most common types of planets from the results of microlensing surveys.

The disk model images presented in this work were obtained considering a distance of 140 pc, which is close to the average distance of young disks in several nearby star-forming regions. In the Ophiuchus, Chamaeleon, and Lupus star-forming regions, 32, 14, and 15 disks have approximately the same total flux density (within 20%) or are brighter than our reference disk model at the wavelengths probed by the observations, i.e., 0.89 or 1.3 mm (Ansdell et al. 2016; Pascucci et al. 2016; Cieza et al. 2019, respectively). At the same time, most of these relatively bright disks are large, with outer radii in the dust emission larger than ≈50–100 au, and the possibility to detect disk substructures at similar S/N to those presented here will critically depend on the brightness of the dust emission within ≈5–10 au from the star. Moreover, it is important to note that the majority of the disks detected in these observational surveys are not spatially resolved at resolutions of 30–50 au, and it is possible that several of them are bright enough at stellocentric radii <10 au to observe the planet-induced structures predicted by our models.

The improved angular resolution of an extended ALMA would also reduce the minimum time interval required to detect proper motions of the disk substructures, e.g., the expected azimuthal motion of the extended arcs as well as of possible circumplanetary disks.

To use an example from our models, we consider the model with $\Sigma_0 = 100$ g cm$^{-2}$ shown in Figure 5, which features a prominent asymmetric structure at an angular stellocentric radius $r = 25$ mas (3.5 au), which is resolvable with the ax54 configuration with ALMA Band 7. The region close to the center of this arc can be well described by an azimuthal Gaussian function $I(\theta) = I_0 e^{-\theta^2/2\sigma^2}$ with parameters $I_0 = 4.2$ Jy arcsec$^{-2}$ and $\sigma = 1.3$ rad from the ALMA Band 7 image. At the peak intensity, the simulations presented here with the ax54 configuration achieve an S/N $I_0/\sigma \approx 15$. The astrometric uncertainty in determining the peak of the Gaussian is then approximately equal to $I_0/\sigma = 2.1$ mas. For a star with mass of $1 M_\odot$, the required time interval to detect the proper motion of this structure at $5 \sigma$ is about 160 days.

In the case of a more compact point-like source such as the case of a circumplanetary disk detected at high S/N (>20, corresponding to flux densities >170 $\mu$Jy in our ALMA Band 7 simulations), the astrometric precision is limited by atmospheric effects. Under nominal observing conditions, the ALMA Technical Handbook states that the best astrometric uncertainty is given by $\sigma_{\text{PSF}}/20$, although because our beam size is also much finer than 0.15, we must further increase this uncertainty by a factor of 2 due to the expected phase decorrelation. This results in an astrometric precision of $\approx 0.6$ mas in ALMA Band 7 with the ax54 configuration. This gives a time interval of 44 days to detect the proper motion at $5 \sigma$ for a bright point source at 3 au from a solar-mass star at 140 pc, or 57 days for a point source at 5 au.

It is worth noting that although the only case of a clear circumplanetary disk known so far (i.e., PDS 70 c, which is at an orbital radius of about 34 au; Benisty et al. 2021) would be detected with our ALMA Band 7 simulations with an S/N $\approx 10$, the S/N of the dust emission from circumplanetary disks is lower.

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Figure 8. Radial profiles of the azimuthally averaged surface brightness at 0.88 mm for the model with $\Sigma_0 = 100$ g cm$^{-2}$, $q = 1 M_\odot/M_\odot$, and $a_p = 2$ au. The blue line is for the model, and the orange and green lines are for the simulated observations with cycle6.10 and ax54 configurations, respectively. Left: radial profiles extracted from the maps obtained with tclean. The error bars were obtained by dividing the standard deviation of the pixel values in each annular region by the square root of the number of synthesized beams fitting within the annular region. Right: radial profiles and error bars obtained with frankenstein.
disks in the inner disk may be expected to be significantly lower. This is because the size of circumplanetary disks is expected to be related to the radius of the Hill sphere, which is proportional to the stellocentric radius. Because the dust emission of these disks is expected to be mostly optically thick, their flux at submillimeter/millimeter wavelengths would scale quadratically with the stellocentric radius.

The disk models considered in our work lack the resolution to include material orbiting the planet in a circumplanetary disk. According to the theoretical calculations presented in Zhu et al. (2018) for the expected flux densities of circumplanetary disks at submillimeter/millimeter wavelengths, our simulated ALMA Band 7 observations with the ax54 configuration would have enough sensitivity to detect at 3σ the dust emission from the disk of a Jupiter-mass planet with mass accretion rate $\dot{M}_p = 10^{-5} M_{\text{Jup}}$ yr$^{-1}$ and a disk radius larger than $\approx 0.05$ au at a distance of 140 pc, under the assumption that the disk heating is dominated by the gas viscosity with $\alpha$ values of either $10^{-2}$ or $10^{-3}$ (see their Figure 2). Under this assumption, the same ALMA Band 7 observations would detect a viscous-heating-dominated disk located at an orbital radius of 5 au from the star around a planet with $M_p M_p > 10^{-7} M_{\text{Jup}}$ yr$^{-1}$ and $M_p > 10^{-5.5} M_{\text{Jup}}$ yr$^{-1}$ for disks with viscosity parameters $\alpha = 0.001$ and 0.01, respectively (see their Figure 4).

Although all the disk models presented here include planets interacting with the gas and dust in the disk, an extended ALMA would probe at sub-astronomical-unit resolution disk regions where different hydrodynamic instabilities have been proposed to drive the transfer of the disk angular momentum. In this context, the disk regions at stellocentric radii $1\text{ au} < r < 10 \text{ au}$ are particularly interesting as various purely hydrodynamic instabilities are predicted to be active, contrary to the case of
magnetorotational instability (e.g., Lyra & Umurhan 2019). At least in some cases, it has been shown that these instabilities can significantly affect the dynamics of the dust and create substructures that can be observed via high-angular-resolution observations in the dust continuum emission at submillimeter/millimeter wavelengths (e.g., Flock et al. 2020; Blanco et al. 2021, for the case of vertical shear instability). Moreover, some radial substructures can be expected if different mechanisms dominate at different radii across the disk as a consequence of their different efficiencies for the angular momentum transport (Pfeil & Klahr 2019).

5. Conclusions

We have evaluated the potential of an upgraded ALMA to observe at sub-astronomical-unit resolution the terrestrial planet-forming regions of young disks in nearby star-forming regions. The upgraded ALMA considered here consists of an array configuration that combines 42 existing antenna pads with 12 new ones within the ALMA concession and the Atacama Astronomical Park and that would double the maximum baseline length ($b_{\text{max}} \approx 32 \text{ km}$). To quantify the effects of this upgrade, we simulated observations of a family of disk models, perturbed by single planets with planet-to-star mass ratios of 1 and 10 $M_\oplus/M_*$, at orbital radii of 1–5 au from the host star, located at a distance of 140 pc.

Our work shows that an extended ALMA would markedly improve upon the detection and investigation of the disk substructures in the dust continuum expected from the interaction between Earth-mass and super-Earth planets and the disk regions of low gas viscosity. In particular, gaps associated with super-Earth planets with $q = 10 M_\oplus/M_*$ can be detected as close as 1 au (7 mas) from the star, and azimuthally asymmetric structures can be resolved in disks with relatively low density. Evidence of gaps produced by Earth-mass planets with $q = 1 M_\oplus/M_*$ can be identified at stellocentric distances as short as $\approx 2$–3 au through an analysis of the interferometric visibilities, as shown here using the frankenstein code.

An extended ALMA would also allow more accurate measurements of the main properties of gaps, e.g., radial widths and depletion factors, at radial distances down to $\approx 2$–3 au from the central star. These observations would provide more accurate estimates of planet properties from the data-model comparison. A broader parameter space of planets could be investigated in this way, which would better overlap with the distribution of exoplanets observed around mature stars.

An ALMA upgrade would also be important for synergy with a future Next Generation Very Large Array (ngVLA), which is expected to detect disk substructures at longer wavelengths than those presented here, i.e., 3 mm and longer, at resolutions of few milliarcseconds (Ricci et al. 2018; Harter et al. 2020; Blanco et al. 2021). The combination of ALMA and ngVLA would enable multiwavelength studies at high angular resolution, which can be used to constrain the dust surface densities, temperatures, and grain-size distributions across the disk (e.g., Carrasco-González et al. 2019).

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We investigate here the improvement expected for the dust continuum imaging of one of our disk models when considering the capabilities of the new ALMA Band 6 receivers, which are currently under development (Asayama et al. 2020). These receivers will improve the sensitivity of the current ones by a factor of $\sim \sqrt{2} \approx 1.4$ and will also provide a wider bandwidth by a factor of $\sim 2$. The extended bandwidth will in turn result in an extra improvement on the continuum sensitivity of $\sqrt{2} \times$, and will also provide better imaging fidelity thanks to the additional sampling of the interferometric $(u,v)$ space by spreading out the frequency coverage.

To simulate the results of future ALMA observations with the extended a×54 configuration and with the new ALMA Band 6 receivers, we adopted the following procedure. We considered the disk model with $\Sigma_0 = 100 \text{ g cm}^{-2}$, $q = 10 M_\oplus/M_*$, and $d_p = 3$ au at a central frequency of 240 GHz (top row in Figure 9, with maps that are shown also in the left three maps in Figure 10). Whereas all the simulated observations presented in our work considered a total bandwidth of 7.5 GHz within a single spectral window, here we simulate observations in four spectral windows centered at 231, 233, 247, and 249 GHz, respectively, with bandwidth for each window of 1.875 GHz, for a total bandwidth of 7.5 GHz. For each central frequency of each window, we calculated an image from our disk model, using the same method as described in Section 2.1, in order to take into account the variation with frequency of the dust emission from the disk model. These images were then combined in our ALMA simulations via the multiterm multifrequency method with nterms=2 in tclean. Other than providing a more accurate representation of the dust emission across the bandwidth sampled by the observations, this procedure has the main advantage of obtaining better image fidelity thanks to the additional coverage of the $(u,v)$ space. The result of this simulation is shown in the fourth map from the left in Figure 10. The comparison with the third map in the same figure shows the modest changes with respect to the image obtained in Section 3, which considered a single spectral window, and no variation with frequency of the disk emission.

A significant improvement is obtained when the same procedure was used to simulate the observations with the upgraded Band 6 receivers. To account for the 2 × wider bandwidth, we considered four spectral windows centered at 230, 234, 250, and 254 GHz, respectively, and each with a bandwidth of 4 GHz (total bandwidth of 16 GHz). In order to reproduce the additional improvement to the receiver sensitivity of $1.4 \times$ without introducing any extra $(u,v)$ coverage, we simulated the same observation twice, with

\[ \text{http://science.nrao.edu/facilities/alma/alma-develop-old-022217/2ndGen20Band0206%20Rcvr} \]
different seed parameters in simobserve to get different noise characteristics for the two simulations. We then concatenated the visibility data sets from these two simulations and imaged the interferometric visibilities with the multiterm multifrequency method in tclean as described above. The rightmost map in Figure 10 displays the clear improvement in S/N fidelity of the most prominent disk substructures predicted by the model.

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