OBSERVATIONAL SIGNATURES OF PLANETS IN PROTOPLANETARY DISKS I: GAPS OPENED BY SINGLE AND MULTIPLE YOUNG PLANETS IN DISKS

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ABSTRACT

It has been suggested that the gaps and cavities recently discovered in transitional disks are opened by planets. To explore this scenario, we combine two-dimensional two fluid (gas + particle) hydrodynamical calculations with fully three-dimensional Monte Carlo Radiative Transfer simulations and study the observational signatures of gaps opened by one or several planets, making qualitative comparisons with observations. We find that a single planet as small as 0.2 $M_J$ can produce a deep gap at millimeter (mm) wavelengths and almost no features at near-infrared (NIR) wavelengths, while multiple planets can open up a few $\times 10$ AU wide common gap at both wavelengths. Both the contrast ratio of the the gaps and the wavelength dependence of the gap sizes are broadly consistent with data. When viewed at a moderate inclination angle, a physically circular on-centered gap could appear to be off-centered from the star due to shadowing. This effect can be used to check the existence of an unseen inner disk. Planet-induced spiral arms are more apparent at NIR than at mm wavelengths. Overall, our results suggest that the planet-opening-gap scenario is a promising way to explain the origin of the transitional disks. Finally, inspired by the recent ALMA release of the image of the HL Tau disk, we show that multiple narrow gaps, well separated by bright rings, can be opened by 0.2$M_J$ planets soon after their formation in a relatively massive disk.

Subject headings: protoplanetary disks — stars: pre-main sequence — radiative transfer — circumstellar matter

1. INTRODUCTION

Flattened, rotating gaseous protoplanetary disks around young stars reprocess light from the central star, modifying the spectral energy distribution (SED) of the system, and revealing themselves in resolved images at various wavelengths (Williams & Cieza 2011). These disks are considered to be the birth place of planets (Armitage 2011). Ideally, detecting newly-born planets in protoplanetary disks directly is one of the best ways to constrain planet formation, as it can reveal when, where, and how do planets form. However, the common techniques such as radial velocity and transit observations are more difficult to apply due to the intrinsic variability of pre-main sequence stars. With direct imaging, the planets are difficult to detect against the bright background of the circumstellar disks. Therefore, methods for indirect detection of young planets in disks are necessitated.

In a circumstellar disk, planets excite asymmetric structures such as spiral density waves, and may clear material around their orbits to form gaps, through gravitational disk-planet interactions (Kley & Nelson 2012). While directly detecting planets in disks is hard, these large scale planet-induced distortions are more prominent, and may be detectable in high spatial resolution (e.g. Wolf & D’Angelo 2005; Varnière et al. 2006a; Jang-Condell & Boss 2007; Jang-Condell et al. 2009; Jang-Condell & Turner 2012; Gonzalez et al. 2012; Ruge et al. 2013; de-Juan Ovelar et al. 2013). By identifying and comparing these features with theoretical models of disk-planet interactions, we can learn much about the possibly embedded planets.

The last few years have witnessed ground breaking results in resolved observations of protoplanetary disks, and fine structures possibly produced by planets have been found in many systems at multiple spectral windows. At near-infrared (NIR) wavelengths, more than a dozen nearby disks have been imaged by 10-meter class mirrors, in particular VLT (e.g. Quanz et al. 2011, 2012; Canovas et al. 2013; Quanz et al. 2013; Garufi et al. 2013; 2014; Kovacevich et al. 2013; Avenhaus et al. 2014) and Subaru (the Subaru Strategic Exploration of Exoplanets and Disks Survey, Tamura 2009, Tsukagoshi et al. 2014; Takami et al. 2013; Follette et al. 2013; Grady et al. 2013; Tanii et al. 2012; Mayama et al. 2012; Kusakabe et al. 2012; Muto et al. 2012; Hashimoto et al. 2011). These observations took advantage of the Polarimetric Differential Imaging technique (PDI, Hinkley et al. 2009) to effectively remove the unpolarized stellar light while retaining the polarized component in the scattered light from the dust grains in disks. Inner working angles (the smallest angular separation from the central source to which NIR observations have access) on the order of 0.1" and diffraction limited angular resolution $\sim 0.04$–$0.06$" at $J, H, K$ bands have been routinely achieved (corresponding to $\sim 14$ AU and $\sim 6$–$8$ AU at the distance of nearby star forming regions, $\sim 140$ pc, such as Taurus).

Accompanying the progress in NIR direct imaging, radio interferometry has opened up another window lately around $\sim 1$ mm for detailed disk structure studies. Spa-
tially resolved observations of dust continuum and/or molecular line emission have been carried out for a few dozens nearby disks using the Submillimeter Array (e.g. Brown et al. 2009; Andrews et al. 2009; 2010; 2011), the Combined Array for Research in Millimeter-wave Astronomy (e.g. Isella et al. 2009; 2010; Ricci et al. 2013), the Plateau de Bure Interferometer (e.g. Pietu et al. 2006; Guilloteau et al. 2011), and the newly commissioned Atacama Large Millimeter Array (ALMA) (e.g. van der Marel et al. 2013; Casassus et al. 2013; P´erez et al. 2014; Zhang et al. 2014). Protoplanetary disks are generally optically thick at NIR, so NIR imaging traces the surface structure (e.g. Takami et al. 2014). On the other hand, they are often optically thin in mm dust continuum and certain molecular line emissions, so mm observations can probe the distribution of material in the midplane regions of disks. As ALMA is transitioning into its full capacity phase in the next few years, it will provide more exciting results with its sub-0.1′′ angular resolutions and superb sensitivity.

Among disks with possible planet-induced structures, a particularly interesting group is the so called transitional disk. Discovered through their unique infrared deficit from NIR to ~ 10 μm, which signals a lack of warm dust in the inner disk (Calvet et al. 2005; Espaillat et al. 2007; 2010), these have been subsequently shown to harbor large gaps or cavities with sizes often up to tens of AU in spatially resolved observations (e.g., Thalmann et al. 2010; Mayama et al. 2012; Hashimoto et al. 2012; Hughes et al. 2009; Andrews et al. 2011; Zhang et al. 2014; Perez et al. 2014). The appearances of transitional disks are not always consistent at different wavelengths. In some cases, NIR images do not show the cavities seen at mm down to their inner working angle (Dong et al. 2012b), while in some other cases the cavities in scattered light and/or gas observations appear to be smaller than in the dust continuum (e.g. Garufi et al. 2013; Zhang et al. 2014; Perez et al. 2014). The formation of the gap/cavity in transitional disks is not well understood at the moment. Several mechanisms can partially explain the observations, including grain growth (Dullemond & Dominik 2005; Birnstiel et al. 2012), photoevaporation (Alexander & Armitage 2007; 2009; Owen et al. 2012; Rosotti et al. 2013), infall from counterrotating external environments (Vorobyov et al. 2014), and of particular interest, disk–planet interactions (Bryden et al. 1999; Varnière et al. 2006b). While the gap opened by a single planet may be too narrow to match observations, a system of several giant planets may open a combined/common gap with a size comparable to observed values. Zhu et al. (2011) and Dodson-Robinson & Salyk (2011) performed two-dimensional (2D) hydro disk–planet simulations, and found that a system with 4 planets can indeed open a wide gap in the gas surface density and still maintain a moderate accretion rate onto the star as observed in some systems. More recently, dust particles have been added into these models. Zhu et al. (2012) and Pinilla et al. (2012) have shown that the “dust filtration” effect (Paardekooper & Mellema 2006; Rice et al. 2006) may allow the cavity in the gas and dust to have different sizes. The is because the pressure maximum at the gap edge created by a planet can efficiently pile up the big grains with a stopping time close to unity and prevent them from entering the gap, while still allowing gas and smaller size grains to move into the gap.

While exciting progress has been made in both theory and observations in recent years, a relatively underdeveloped region is the linkage between the two. Numerical hydro or magnetohydrodynamic (MHD) simulations (e.g. Zhu et al. 2014b; Zhu & Stone 2014) calculate density structures for gas and/or dust particles, and it is a non-trivial process to “translate” them into corresponding model observations such as images at various wavelengths. For example, to produce mm dust continuum emission images assuming the disk is optically thin, a temperature profile and a prescription for the dust properties are needed, as the intensity at frequency ν is Iν ∝ κνΣgrains, where κν is the dust opacity at ν and Σgrains is the surface density of the grains. It it even more complicated to produce scattered light images, as scattered light profile is largely determined by the shape (curvature) the disk surface, which is set by the 3D density distribution of the small grains in a sophisticated manner (Takami et al. 2014). In addition, a treatment of polarized dust scattering is needed to produce PI images. As a result, radiative transfer modeling is needed in order to generate accurate model observations for hydro/MHD disk models.

This paper is the first in a series in which we explore various observational signatures of planets in protoplanetary disks. We intend to bridge the gap between theory and observation, by combining tools of hydro/MHD calculations with 3D Monte Carlo Radiative Transfer (MCRT) simulations. Specifically, in order to directly translate hydro/MHD simulations into model observations, we use the Whitney et al. (2013) code to read in an external numerical density grid and calculate the radiative transfer. In this study, we focus on gaps opened by one and multiple planets, and aim at answering this basic question: are they broadly consistent with observed gaps in transitional disks? This topic has been explored by de Juan Ovelar et al. (2013), who pointed out that dust filtration could pile up big grains at the edge of the gas gap opened by one giant planet to form a ring at mm wavelengths, while allowing small grains to enter the gap to produce scattered light. Recently, Pinilla et al. (2014) expanded the work to have two planets at a large separation, which opened two non-overlapping gaps. In both studies, the authors ran hydro simulations to calculate 2D gas surface density, and fed it into 1D dust evolutionary models to calculate the radial distribution of grains. As a result, only axisymmetric model images were produced by 2D (radial-polar) MCRT simulations, and azimuthal features, such as spiral arms, were not followed. In this work, we combine 2D (radial and azimuthal) two fluid (gas + particle) hydro calculations with fully 3D MCRT simulations, in which the 3rd dimension is the height of the disk that we calculate prior to reading into the MCRT code. Images at both NIR and mm wavelengths are produced and compared with observations. The paper is organized as follows. In Section 2 we introduce our hydro and MCRT methods. The main results are presented in Section 3. We discuss our results

0.3-3 mm wavelengths “mm observations”
Gaps Opened by Multiple Planets in Protoplanetary Disks

2. SIMULATION SETUP

2.1. Hydrodynamical Gas+Dust Simulations

We have carried out global 2D two-fluid hydrodynamical simulations using the FARGO code (Masset 2000) with a newly implemented dust fluid (Zhu et al. 2012). The dust is treated as a zero pressure fluid and couples with the gas via drag terms. No feedback from the dust on the gas is considered since gas-to-dust mass ratio is always much larger than 1 in our simulations. The drag terms are computed by assuming the dust is in the Epstein regime (Whipple 1972; Weidenschilling 1977), which is always true for our adopted particle sizes and disk parameters. At the disk midplane, the dust stopping time in the Epstein regime can be written as

\[ t_s = \frac{\pi \rho_\text{p}}{2 \Sigma_\text{g} \Omega}. \]

When the dust’s stopping time is much shorter than the disk’s dynamical timescale, we can use the Short Friction Time Approximation (SFT, Johansen & Klahr 2005) to calculate the dust velocity:

\[ v_\text{d} = v_\text{g} + t_s \frac{\nabla P}{\Sigma_\text{g}}. \]

where \( P \) is the gas pressure. This approximation is always true for our chosen particle size (more discussion and the detailed comparison with other approaches are given in the Appendix of Zhu et al. 2012). Dust turbulent diffusion is modeled as a diffusion term in the dust continuity equation. The Schmidt number \( Sc \), which is defined as the ratio between the total accretion stress and particle mass diffusivity, is assumed to be 1 (Johansen & Klahr 2005).

Hydrodynamical model setups are largely adopted from Zhu et al. (2011), and are briefly summarized here. We assume a central stellar mass of 1\( M_\odot \) and a fully viscous disk. We further assume a radial temperature distribution \( T = 221(r/\text{AU})^{-1/2} \) K, which is roughly consistent with typical T Tauri disks in which irradiation from the central star dominates the disk temperature distribution (e.g. D’Alessio et al. 2001). The disk is vertically isothermal, and the scale height is \( h_\text{g} = c_s / \Omega \), where \( c_s \) is the sound speed and \( \Omega \) is the orbital frequency. The adopted radial temperature distribution corresponds to \( h_\text{g}/r = 0.029(r/\text{AU})^{0.25} \) assuming vertical hydrostatic equilibrium. We set \( \alpha = 0.001 \). With this \( \alpha \), the gap edge will develop vortex only if massive planets are in the disk and the vortex can quickly dissipate (Zhu & Stone 2014; Fu et al. 2014). This is consistent with that no vortex is observed at the end of all current simulations. The initial gas surface density is

\[ \Sigma_\text{g} = 178 \frac{\text{AU}}{r} e^{-\frac{r}{\text{sub}}} \text{ g cm}^{-2}, \]

from \( r \approx 1 - 500 \) AU, so that it reaches a steady disk solution with an accretion rate \( \dot{M} \sim 10^{-3} M_\odot \text{yr}^{-1} \), typical of T Tauri disks (Gullbring et al. 1998; Hartmann et al. 1998). The dust particles are assumed to be 1 mm in radius. The surface density of the particles \( \Sigma_\text{p} \) is set to be 0.01 \( \times \Sigma_\text{g} \) at the beginning of the simulations. Since dust is treated as a passive fluid, we can scale the dust surface density later using a realistic 1 mm dust-to-gas mass ratio. The simulations have 256 grid cells in both radial (1-500 AU) and azimuthal (\( 2\pi \)) directions. In total we carry out five simulations. Their setups are shown in Table 1. The two \( 1 \times M_\odot \) (\( x \) represents the mass of planets in the model names) runs have 1 planet, the two \( 4 \times M_\odot \) runs have 4 planets, and Model 3 \( 3 \times 0.2 M_\odot \) has 3 planets. Accretion of disk material onto planets are not included in our models, and the radial locations of the planets are fixed so they don’t migrate in the disk (this assumption will be discussed in Section 4.3). Planets in all models are on circular orbits. For the first 4 models, each of the neighboring pairs in the 4-planet models are locked into 2:1 resonances. These 4 models are evolved for 0.4 Myr, at which point \( \Sigma_\text{g} \) has reached a steady state, while \( \Sigma_\text{p} \) at the peak of the ring outside the outermost planet changes less than 5% in the last 10% of time (\( \Sigma_\text{p} \) in models with \( \geq 1 M_\odot \) planets has touched a hard floor inside the gaps in the hydro simulations). The final gas disk mass of these models are in between 0.03\( M_\odot \) and 0.04\( M_\odot \).

2.2. Monte Carlo Radiative Transfer Simulations

We carry out 3D MCRT simulations using the code developed by Whitney et al. (2013) see also Whitney et al. 2003a, 2003b. We focus on images at \( H \) band and ALMA band 7 (continuum emission at 870 \( \mu \)m); SEDs and images at 10 \( \mu \)m and 100 \( \mu \)m are presented as well. This code has been used to model protoplanetary disks in the past (e.g. Hashimoto et al. 2012; Zhu et al. 2012; Dong et al. 2012). Follette et al. 2013; Grady et al. 2013).

The disk setup is largely adopted from Dong et al. (2012b). We construct a 3D disk structure in spherical coordinates. The number of grid cells in the radial (\( r \)), azimuthal (\( \phi \)), and polar (\( \theta \)) directions are 400, 257, and 201, respectively. All simulations are run with 4 billion photon packages. The central source is a 1 \( M_\odot \), 4500 K pre-main-sequence star with a surface gravity \( g = 10^4 \text{ m/s}^2 \) and solar metallicity. The inner boundary of the disk is at the dust sublimation radius where the dust temperature reaches 1600 K (\( r_{\text{sub}} \sim 0.1 \text{ AU} \)), while the outer boundary is at 500 AU.

There are two disk components in our models – a “small” dust particle size disk, and a “big” dust particle size disk. The grains in the small dust disk (“small grains” from now on) are the standard interstellar medium (ISM) grains as in Kim et al. (1994), sub-\( \mu \)m-sized or smaller. The grains in the big dust disk (“big grains” from now on) are assumed to have the same chemical compositions as the ISM grains, but with a number density \( n(s) \) dependence on the grain size \( s \) going as \( n(s) \propto s^{-3} \). The minimum and maximum grain sizes are assumed to be 900 \( \mu \)m and 1.1 mm, and the opacity, albedo, average cosine scattering angle, and maximum polarization are calculated using the routine developed by Bohren & Huffman (1983). We use these

\footnote{In this work, the physical quantity recorded in all model images is the specific intensity, or intensity \( I_\nu \) for short, which has the unit [mJy arcsec\(^{-2}\)].}

\footnote{We use the version of the Bohren & Huffman}
grains to represent the 1 mm dust particles in the hydro simulations.

We directly read in the 2D gas and particle surface density from our hydro simulations to set up MCRT models. In general, the small grains are strongly coupled to the gas due to their short stopping time. Therefore, the surface density of the small grains $\Sigma_{sg}$ is assumed to be linearly proportional to $\Sigma_g$, while the surface density of the big grains $\Sigma_{bg}$ scales with $\Sigma_p$. Specifically, we set $\Sigma_{bg} = 0.9 \Sigma_g$ and $\Sigma_{sg} = 10^{-3} \Sigma_g$ (initially $\Sigma_p = 0.01 \Sigma_g$, see Section 2.1). In this way, the initial gas-to-dust mass ratio at $t = 0$ in the hydro calculations is $100 : 1$, a canonical value assumed in protoplanetary disks, and the initial big-to-small-dust mass ratio is $9:1$. These ratios change as the distribution of gas and particles are evolved independently in hydro calculations, though changes are small in our models as the final gas-to-dust ratio always stays within $20\%$ from the initial value ($100:1$). We note that observational results have shown that the gas-to-dust mass ratio can be quite low (as low as $\sim 20$) in some Class II disks (Williams & Best 2014). Also, the choice of the big-to-small-dust mass ratio is somewhat arbitrary. In reality, any number from $\sim 0$ (the ISM value) to $\infty$ (solids completed converted to planetesimals) may exist. Our choice of $9 : 1$ just represents a non-special middle stage. Under this ratio, the NIR and mm images are more or less independently determined by the distribution of small and big grains separately, easing the analysis of the model results. As a consequence, absolute values of $\Sigma_{sg}$ and $\Sigma_{bg}$ and the resulting absolute intensities of the images should be taken as references only. Future observations with better fidelity and angular resolution have the potential to measure the location dependent big-to-small dust mass ratio. In the disk radius range that is covered by the hydro calculations, we map the 2D hydro grid onto the 2D MCRT grid with a second order interpolation scheme. For the inner disk that is not covered by the hydro models ($r_{\text{nhub}} \leq r < 1 \text{ AU}$), we extrapolate the surface density at the inner boundary of the hydro simulations inward.

Once we have the 2D distributions for both grain-model disks, we need to vertically extend the disk to construct 3D structures for the MCRT simulations. This is done by assuming Gaussian profiles for the volume density of both grains in the vertical direction,

$$
\rho_{bg}(z) = \frac{\Sigma_{bg}}{h_{bg} \sqrt{2\pi}} e^{-z^2/2h_{bg}^2},
$$

and

$$
\rho_{sg}(z) = \frac{\Sigma_{sg}}{h_{sg} \sqrt{2\pi}} e^{-z^2/2h_{sg}^2},
$$

where $h_{bg}$ and $h_{sg}$ are the scale height of the small and big grains, respectively. As small grains are well mixed with the gas, $h_{sg} = h_g$. On the other hand, big grains tend to settle toward the disk mid-plane, and their vertical distribution is determined by the balance between gravitational settling and turbulent diffusion. As in (Cuzzi et al. 1993) and (Youdin & Lithwick 2007),

$$
h_{bg} = \frac{h_g}{\sqrt{1 + T_s Sc/\alpha}}
$$

where the dimensionless stopping time $T_s = t_s \Omega$. We set $\alpha = 0.001$ and $Sc = 1$ as in the hydro models (Section 2.1). We caution that in MRI turbulent disks dominated by ambipolar diffusion, $Sc$ can be larger than $1$ (Zhu et al. 2014a).

The raw model images directly produced by the MCRT simulations (i.e. full resolution images) need to be convolved by a point spread function (PSF) in order to achieve an angular resolution comparable to observations. We convolve the $H$ band images using a circular Gaussian kernel with a full width half max (FWHM) of $0.04''$ ($6 \text{ AU at } 140 \text{ pc}$), as a good approximation to the angular resolution achieved by Subaru, VLT, and Gemini with their high contrast imaging systems (the FWHM of an airy disk is $1.028/\lambda \sim 0.04''$ for a primary mirror with a diameter $D = 8.2 \text{ m at } \lambda = 1.6 \mu m$). Model images at ALMA band 7 are convolved by a Gaussian kernel with a FWHM of $0.1''$ (i.e. a $0.1'' \times 0.1''$ beam, $14 \text{ AU at } 140 \text{ pc}$), a typical beam size routinely achievable by ALMA in the near future. The source is assumed to be at a distance of $140 \text{ pc from earth}$.

\section{Results}

In this section, we present results from the hydro and MCRT simulations for Models $1 \times 0.2M_J, 1 \times 1M_J, 4 \times 1M_J$, and $4 \times 2M_J$ (Model $3 \times 0.2M_J$ will be discussed separately in Section 4.2), including surface density maps for both grain models, and images at two inclinations for $H$ band and ALMA band 7 (continuum at $870 \mu m$). The SEDs and raw images at $10 \mu m$ and $100 \mu m$ are shown in Appendix A. Throughout the paper, we use “blue-hot” color scheme for small grains and scattered light related presentations, and “red-hot” color scheme for big grains and dust thermal emission related presentations.

\subsection{Density Structure of the Models}

The 2D surface density distribution for both the big and small grains are shown in Figure 1 and their azimuthally averaged radial profiles are shown in Figure 2. Gap property measurements are listed in Table 2. In Models $1 \times 1M_J, 4 \times 1M_J$ and $4 \times 2M_J$, $\Sigma_{\text{min, gap}}$ is $\geq 10^5$ for the big grains due to a strong dust filtration effect (the dimensionless stopping time $T_s$ is around 0.4 for 1 mm particles at the outer gas gap edges) while it is only $\sim 1.5$ orders of magnitude for the small grains. In Model $1 \times 0.2M_J$, where we have a $0.2M_J$ planet, the gap is almost flat in the small grains, while still more then 3 orders of magnitude deep in the big grains.

The width and position of the gap depends on the configuration of the planetary system. In the small grains, note that $\Sigma_{bg}$ has a hard floor in the hydro simulations in order to keep the runs stable, so $\Sigma_{bg}$ for the big grains could be higher.
a narrow or almost no gap is opened up in the single-planet models, as small grains are allowed to cross the orbit of the planet and populate the inner disk. In contrast, gaps opened by each of the individual planets in the four-planets models overlap with each other and form a wide common gap. For the big grains, the gas pressure bump outside the outermost planet’s orbit in all 4 models effectively traps the grains and piles them up. Increasing the mass of the planets in the 4 × M1 models from 1Mj to 2Mj causes the gas gap to become wider and the edge becomes sharper, so the “ring” in the big grains becomes wider and moves outward. Also, in Model 4 × 2Mj, the gap is slightly eccentric, as a result of the disk-planet interaction in the high planet mass regime (Kley & Dirksen 2006; D’Angelo et al. 2006; Ataiee et al. 2013; Pinilla et al. 2014). In all three cases with Mp ≥ MJ, density waves from the planets and streamers inside the gap are clearly visible in Σbg, while they are only marginally traceable in the distribution of big grains in some cases (e.g. Model 4 × 1Mj).

To illustrate the dust settling effect, the vertical density structure of both grains in Model 1 × 1Mj at φ = 0° is shown in Figure 3. While the small dust disk has a flared structure, the big grains collapse to the mid-plane, especially at regions where Σg is low. Within the gap, the gas surface density drops significantly, leading to an even larger Tc and smaller hpd.

3.2. Face-on Disk Images

Figure 4 shows the face-on MCRT model images (i.e. at a viewing angle θ = 0°) at both H band (polarized intensity) and ALMA band 7 (continuum emission at 870 μm). The azimuthally averaged radial profile of these images are shown in Figure 3 and measurements of the gap properties are listed in Table 3.

The gap width at the two wavelengths are very different. The mm images have a similar structure in all models: a bright ring and a centralized peak. The mm images do not have this asymmetry. In addition, the bright elliptical ring is off center from the star. This is due to shadowing and geometric effects. To illustrate these effects, we run a control model that has the same density structure with Model 4 × 1Mj at r ≥ 35 AU, but no material inside 35 AU (4 × 1Mj-empty-gap), and compare H band images of the two in Figure 8. The raw image of Model 4 × 1Mj (the upper left panel) reveals a dark lane in the middle on the far (top) side of the gap wall (indicated by the arrow). This is because the material inside the gap, including the residual inner disk, spiral arms, and streamers, block the starlight from reaching the middle part of the gap wall. Due to the low surface density in the gap region and the flaring of the disk, the inner disk does not block the starlight from reaching the upper and lower part of the wall. Consequently, when convolved, the bright ring

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11 Model images are binned into annuli with a width of ~2 AU

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the outer disk (I_{max, out}) to the minimum value inside the gap (I_{min, gap}), and list the measurements in Table 3. At H band, c_{image, conv} are only around 3-6 for all models with M_p ≥ Mj, comparing with ~ 100 – 1600 at mm wavelengths. The gap contrast difference in the raw images are even bigger.

Another feature at H band is the visibility of density waves and streamers. They are very clear in raw images, and still traceable in convolved images with less contrast (particularly in Model 4 × 2Mj, in which the surrounding gap region is fainter than the other models, Figure 6). On the other hand, spiral density wave are less evident at mm wavelengths than at NIR wavelengths. Spiral arm like features have been found in scattered light images in recent years (e.g. Muto et al. 2012; Grady et al. 2013), and yet their origins are still largely unknown. We defer a detailed study of the appearance of the spiral arms to the next paper.

Lastly, the gap sizes in the model images depend on wavelength, as pointed out by de Juan Ovelar et al. (2013) and Pinilla et al. (2014). The radii of the peak intensities in the outer disk in the azimuthally averaged convolved images are indicated in Figure 5, convolved images are listed in Table 3 as r_{max, conv, image}. In all cases, the peak in the mm is at a larger radius than at H band. In addition, the difference between them increases as the mass of the planets increase from Model 4 × 1Mj to Model 4 × 2Mj. Note that this is not due to the difference in the locations of the peak surface density in the outer disk in the two grains, as r_{max, out, Σ} is actually slightly smaller in Σbg than in Σg (Figure 4 and Table 3). This difference is mainly caused by a radiative transfer effect. As the mm emission linearly scales with Σbg, r_{max, out, image} at mm wavelengths closely traces r_{max, out, Σ} in the big grains. On the other hand, the NIR scattered light more closely traces the abrupt changes in Σbg, as they lead to sudden variations in the shape (curvature) of the disk surface. As a result, the H band images peak around the outer gap edge in Σbg, not r_{max, out, Σ} in the small grains.

3.3. Inclined Disk Images

Figure 7 shows model images at a viewing angle θ = 45°. The H-band images show a large scale asymmetry along the minor axis: the top (far) side of the disk appears to be fainter than the bottom (near) side of the disk. This is due to forward scattering from the dust particles in an inclined disk (face on images and inclined mm images do not have this asymmetry). In addition, the bright elliptical ring is off center from the star. This is due to shadowing and geometric effects.

To illustrate these effects, we run a control model that has the same density structure with Model 4 × 1Mj at r ≥ 35 AU, but no material inside 35 AU (4 × 1Mj-empty-gap), and compare H band images of the two in Figure 8. The raw image of Model 4 × 1Mj (the upper left panel) reveals a dark lane in the middle on the far (top) side of the gap wall (indicated by the arrow). This is because the material inside the gap, including the residual inner disk, spiral arms, and streamers, block the starlight from reaching the middle part of the gap wall. Due to the low surface density in the gap region and the flaring of the disk, the inner disk does not block the starlight from reaching the upper and lower part of the wall. Consequently, when convolved, the bright ring
roughly overlaps with the upper edge of the gap wall, which is not at the same plane as the star (upper right panel). Therefore, if fitting the ring by an ellipse (the dashed red ellipse), the center of the ellipse offsets from the star (marked as `×`). In our example here, the offset is \( \sim 8\% \) the length of the minor axis, or \( \sim 12\% \) of the gap radius. On the other hand, in Model \( 4 \times 1 M_J \)-empty-gap, the entire outer gap wall is uniformly illuminated (i.e. no dark middle lane on the far side, lower left panel), and the center of a fitted ellipse to the ring in the convolved image almost coincides with the star (lower right panel: a small offset along the minor axis still exists as the near and far sides of the gap wall are still not exactly symmetric due to geometric effects).

4. DISCUSSION

4.1. Comparison between Model Results and Observations

To date, a number of transitional disks have been resolved at NIR and/or mm wavelengths. Here we compare the morphology and properties of the observed systems with our models (Model \( 3 \times 0.2 M_J \) will be discussed separately in Section 4.2), aiming at answering the basic question of whether gaps opened by single or multiple planets are broadly consistent with observations or not.

4.1.1. Appearance of the Gap

The global appearance of the gap at NIR is affected by the size of the inner working angle \( \psi_{in} \) in NIR imaging, which is typically \( \sim 0.1'' \sim 0.2'' \) with current technology. Scattered light images of Model \( 1 \times 1 M_J, 4 \times 1 M_J \) and \( 4 \times 2 M_J \) all have a gap. However, if observed with current NIR imaging facilities, these models may appear to have a gap, a cavity, or no gap or cavity in the observations, depending on the relative gap size compared with \( \psi_{in} \):

\[
\psi_{in} < r_{gap,in,image}: \text{Gap} \\
r_{gap,in,image} \leq \psi_{in} \leq r_{gap,out,image}: \text{Cavity} \\
r_{gap,out,image} \leq \psi_{in}: \text{No gap or cavity}
\]

At mm wavelengths, formally all 4 models produce a gap instead of a cavity, in the sense that the disk has a emission peak at the center due to the presence of grains in the inner disk. The brightness of the inner disk varies with the planet-disk configuration, from being as bright as the ring in Model \( 1 \times 0.2 M_J \) to about 1/10 of the surface brightness of the ring in Models \( 4 \times 1 M_J \) and \( 4 \times 2 M_J \). However, depending on the instrument sensitivity, the emission from the inner disk may or may not be detectable at mm observations, and the disk may appear to have a gap or a cavity accordingly (the \( 1 \times 0.2 M_J \) case would almost certainly appear to be a gap system if resolved). Lastly, we note that the central emission is largely influenced by grain growth and evolution in the inner disk, which may decrease or increase the amount of mm-sized grains there dramatically. We defer the exploration of these effects to future studies.

4.1.2. Gap Width

The giant gap/cavity revealed in NIR imaging of a few transitional disks (e.g. RX J1604.3-2130, Mayama et al. 2012, HD 142527, Canovas et al. 2013, SAO 206462, Garufi et al. 2013 and PDS 70, Hashimoto et al. 2012) are all quite large, ranging from \( \sim 28 \text{ AU} \) in SAO 206462 to over 100 AU in HD 142527. As the width of the NIR gap opened by a 1\( M_J \) planet at 30 AU in our model is only 10 AU, the single-planet scenario faces major difficulties in explaining observations. Note that having a bigger planet is not a good solution as \( \Delta_{\text{gap}} \) only depends on \( M_p \) weakly. As Fung et al. (2014) pointed out, \( \Delta_{\text{gap}} = 2 \times \max(R_{Hill}, h_g) \) where \( R_{Hill} \propto r_p M_p^{1/3} \) is the Hill radius of the planet (see also Figure 5 in Dutelle & MacFadyen 2013). The observed gap widths are more consistent with our four-planets models (Table 3). We note that as the size of the gap depends on the location of the planets, \( R_{Hill} \propto r_p, h_g \propto r^{1+\delta} \), where \( \delta \sim 0.25 \), shifting planets outward will increase the gap sizes.

4.1.3. Gap Depth

The gap depth in observations is determined by the configuration of the planets, the properties of the disk, radiative transfer processes, and image convolution in a complicated way, as illustrated by a schematic flow chart in Figure 2. We compare the gap contrast in the two 4-planet models with observed systems in Table 4 which are measured in a similar manner as our models. The quoted values and errors are the average and standard deviation over different azimuthal angles. We note that in three out of four observed systems (except HD 142527) the possible inner edge of the gap (if there is one) is not detected as it is blocked by the inner working angle; therefore the measured value for these systems should be considered as a lower limit. On the other hand, observational noise, which may reduce the contrast of the images, is not added in our model images, so the measured values may be upper limits (Monte Carlo images have also, but it may be lower than the observations). Nevertheless, our models show promising agreement with observations.

In the mm/mm interferometric observations, the gap contrast has to be constrained through model fitting of the disk visibility. In the past, the thermal emission inside the gap was often not resolved and in most cases was below the noise floor set by the instrument sensitivity. In these systems, mm data can only provide weak upper limits on the gap contrast in either the emission intensity or \( \Sigma g \). For example, 11 out of 12 objects in Andrews et al. (2011) fell into this category (with the exception of LkCa 15, which has an unresolved but robust centralized peak detection), which only enabled the authors to place lower limits of 10-100 on the depletion of big grains inside the gaps. Our model results (\( \Sigma C \sim 9 \) orders of magnitudes or more in the big grains, Figure 2) are certainly consistent with these lower limits.

This situation is changing as ALMA is starting to detect and spatially resolve the “residual” dust emission inside the gap as it is transitioning into final phase. For example, Zhang et al. (2014) determined that the dust surface density inside the gap in RX J1604.3-2130 is \( \sim 100 \) times lower than that just beyond the dust truncation radius, with the assumptions of a specific base surface density profile and a razor sharp gap edge structure. This “depletion factor” stands in between the values we get for the small and the big grains. In reality, dust particles with sizes from sub-µm to pebbles will co-exist in the disk, and the depletion factor based on emission data
Gaps Opened by Multiple Planets in Protoplanetary Disks

4.1.4. Gap Size Dependence on Wavelengths

One class of transitional disks have a clear cavity at mm, but no gap/cavity down to the inner working angle in NIR imaging (e.g. SR 21, Perez et al. 2014; Follette et al. 2014). For these objects, our models suggest two possible explanations involving gaps opened by planets: (1) the NIR gap may be too shallow and/or too narrow to be detectable due to small planet masses (i.e. Model 1 × 0.2MJ, which has almost no detectable gap at NIR and a mm gap with a contrast of ~ 10). (2) The NIR gap may be entirely hidden under the inner working angle. Both concepts have been raised in the past (e.g. de Juan Ovelar et al. 2013), and we confirm these effects with more advanced calculations.

Our models provide a natural explanation to the recently discovered gap size dependence on wavelength, confirming previous results from literature (e.g. Pinilla et al. 2012). RX J1604.3-2130 (Zhang et al. 2014) and SAO 206462 (Garufi et al. 2013) both show a bigger cavity size at mm than at NIR (~ 78 vs ~ 63 AU in RX J1604.3-2130, and ~ 46 vs ~ 28 in SAO 206462), while HD 142527 shows a bigger cavity size in big grains than in the gas (Perez et al. 2014 ~ 140 AU vs ~ 90 AU). This is consistent with the bigger cavity sizes seen at mm than at NIR in our model images (Table 3). For example, in Model 4 × 2MJ the distance between the outermost planet at 30 AU and the outer gap edge is two times higher in the convolved mm image (15 AU) than in the convolved NIR image (8 AU).

4.2. An HL-Tau-Like System with Multiple Separate Gaps

Inspired by the recent release of the ALMA image of the HL Tau disk, we have included an additional disk-planet model, shown as Model 3 × 0.2MJ in Table 4. This model has 3 planets, located on circular orbits at 12, 30, and 65 AU from the star. The initial gas surface density Σg is 5 times higher than the profile assumed for other models (Equation 3), and the system is evolved for a shorter period, 0.2 Gyr, suggested by the relatively high mass (Kwon et al. 2011) and young age of the system (although we only run the hydro simulate to 0.2 Myr, the dust distribution in this model has already reached a steady state). The total gas disk mass is 0.17 Ms at the end of the hydro simulation, and the final gas-to-dust mass ratio is 90:1. The synthetic mm image is convolved by a 0.035″ × 0.035″ Gaussian beam, to match the angular resolution of ALMA observations. The other conditions in the hydro and MCRT simulations are the same as in Section 2. The surface density maps and the synthetic images at both H band and ALMA band 7 are shown in Figure 12, while the radial profile measurements are shown in Figure 13.

In the gas (small dust) disk, the inner two planets each open a shallow, narrow gap around their orbits. The perturbation induced by the outermost planet is only marginal, due to the large dynamical (gap opening) time scale at its large distance. Somewhat deeper but still narrow gaps are opened in the disk of the big grains. The outer-disk-to-gap contrast ratio Cg for big grains is 28 for the innermost gap, 10 for the middle gap, and 2.5 for the outermost gap, much smaller than the other models. This is because the big grains are only marginally coupled to the gas in this case, mostly due to the high gas surface density and the shallowness of the gas gaps opened by low mass planets. The dimensionless grain stopping time Ts is only on the order of ~ 0.01 to 0.001 around the three gap regions. As a result, the depletion of big grains inside the gap is very incomplete, and the piling up of big grains around the gas pressure peak is insignificant. In addition, in contrast to the two 4 × MJ models, the gaps do not overlaps with each other, and they are well separated by more or less unperturbed disk rings. This is mainly due to the large separations between the planets, and the above mentioned weak coupling between the big grains and gas.

The raw mm images of the system at both face-on and 45° inclination angles clearly show 3 narrow gaps, separated by 2 bright rings, and an inner and an outer disk, closely matching the surface density pattern in the big grains as expected. The beam size, 0.035″ × 0.035″ (or ~ 5 AU), is small enough, so the convolved mm images successfully preserve these features. In our specific model, the gap contrasts C_image,conv in the convolved mm image at face-on angle are 1.5, 3.8, and 1.8 from the innermost to the outermost gaps. We note that C_image,conv sensitively depends on the dust-gas coupling effect, which is set by the surface density of the gas in the disk, and also the profiles of the gas gaps opened by planets, which are determined by the mass of the planets, as well as the viscosity and scale height of the disk.

At H band, similar to Model 1 × 0.2MJ, the gaps are clear in the raw images, but are somewhat smeared out and are only marginally visible in the convolved images. Density waves excited by these low mass planets are marginally visible in the raw images, but almost invisible in the convolved images.

4.3. Caveats

In this section we discuss factors that could potentially affect the gap profile which are not included in our hydrodynamical models.

Firstly, the interactions between a planet and the disk could drive the planet to migrate. When protoplanets open gaps in the disk, planets tend to migrate on a time scale set by the disk’s viscosity (type II migration, Ward 1997; Hasegawa & Ida 2013). The migration time scale for planets in our models is typically on the order of ~ Myr or longer, much longer than the gap opening time scale. Therefore, it is safe to ignore the planet migration in the study of the observational signatures of these gaps. Also, when multiple giant planets migrate together in a gaseous disk, they tend to lock each other into 2:1 mean motion resonance (Pierens & Nelson 2008; Zhu et al. 2011). As a result the system tends to be stable from planet-planet interactions.

Secondly, the choice of disk scale height and viscosity will affect the gap depth (Fung et al. 2014). Also, magnetorotational instability (MRI) has been suggested
to take place in some part of a protoplanetary disk and serve as the source of disk viscosity as well as dust diffusion. Comparing with hydro simulations that have the same nominal $\alpha$, gaps opened by planets in MRI simulations tend to be deeper and wider (Nelson & Papaloizou 2003; Zhu et al. 2013). We defer detailed studies of gap morphology dependence on these factors to future studies.

Lastly, accretion of disk material onto planets may happen as planets grow. Allowing planets to accrete from the disk will make a difference on the gap depth, as the material inside the gap may be drained onto the planets in addition to be cleared due to tidal forces. The more efficient accretion is, the cleaner the gap is (Zhu et al. 2011). Planetary accretion may also introduce distortion in the distribution of gas and dust close to the planets (Owen 2014). Since the efficiency of planetary accretion is still largely not well understood, we choose not to take it into account and to focus on the non-accreting cases.

5. SUMMARY

Theoretical studies in the past have shown that multiple planets are able to create wide gaps in the gas surface density (Zhu et al. 2011) and Dodson-Robinson & Salyk 2011), which resemble the appearance of cavities in transitional disks (Espaillat et al. 2014). However, the basic questions of whether these density features can be seen in observations at various wavelengths, and if so, if they are broadly consistent with observed disk properties, have remained largely unanswered. By combining 2D two fluid gas + particle hydrodynamic calculations with fully 3D Monte Carlo Radiative Transfer simulations, we explore observational signatures of gaps opened by one or more planets in protoplanetary disks. We produce images at $H$ band and mm wavelengths with realistic angular resolutions, and compare them with resolved observations of transitional disks.

Overall, the comparisons between models and observations are satisfying, and suggest that the planets-opening-gap scenario is promising to explain the origin of the transitional disks. Our main results are:

1. The dust filtration effect (Rice et al. 2006; Paardekooper & Mellema 2006) is very efficient at piling up the big grains into a ring at the pressure bump outside the gas gap, and evacuating them from the gap. The surface density gap contrast in the big grains between the peak of the ring and the bottom of the gap could be more than 9 orders of magnitude in our models with $M_p \geq 1M_J$, compared with $\sim 1.5$ orders of magnitudes gas/small grains surface density depletion (Figure 12, Table 4).

2. A single planet can open only a narrow gap in the scattered light images, while multiple planets with the same masses can open a giant common gap. In the two models with 1 $M_J$ planets, the gap opened by a one $M_J$ planet at 30 AU is only $\sim 10$ AU wide, while a $\sim 22$ AU gap is opened by four $M_J$ planets with the outermost planet at the same radius (middle rows in Figures 4 and 5).

3. Our models with $M_p \geq 1M_J$ reach gap contrasts $\sim 3$ – 6 at NIR and $\sim 100$ – 1600 at mm, defined as the ratio of the peak intensity in the outer disk (the ring) to the floor intensity inside the gap. Both are broadly consistent with observations (bottom three rows in Figure 12, Table 4).

4. We confirm the possible solutions to the “missing cavity” problem (Dong et al. 2012b) proposed by Zhu et al. (2012) and de Juan Ovelar et al. (2013), and the cavity size dependence on wavelength effect proposed by Pinilla et al. (2012), with more advanced simulations. NIR gaps opened by a 0.2 $M_J$ planet can be too small to be detected with current NIR imaging instruments, while the same planet is still able to create a prominent gap in the big grains due to the dust filtration effects (the top row in Figures 4, 5). In our model with 2 $M_J$ planets, the distance between the gap edge and the outermost planet at 30 AU is twice as large at mm (15 AU) compared to NIR (8 AU), as shown in the bottom row in Figure 5 (see also Table 3). This is mainly due to the effect of radiative transfer, not the difference in the positions of the peak surface density in the small and big grains. This is consistent with the bigger observed gap size at mm than at NIR in systems like RX J1604.3-2130 (Mayama et al. 2012; Zhang et al. 2014) and SAO 206462 (Andrews et al. 2011; Garufi et al. 2013).

5. Density waves and streamers, which are produced in hydro simulations due to disk-planet interactions, can be visible in NIR images (Figure 9) from 3D MCRT simulations. However, they are less apparent or essentially absent in mm images.

6. If an inner disk aligned with the outer disk exists inside the gap, it will cast a shadow on the gap wall, which can be seen in scattered light images at intermediate viewing angles (Figure 8). The absence of this shadow would indicate either no inner disk or a misaligned inner disk, as seen in LkCa 15 (Thalmann et al. 2014). Furthermore, the ring of the gap edge will appear to be off-center from the star due to this geometric effect. Therefore, off-centered elliptical rings in scattered light images do not necessarily correspond to physically elliptical or off-centered gap structure.

7. Multiple narrow gaps well separated by more or less unperturbed disk rings in both big and small grains can be opened by sub-Jupiter mass planets quickly after their formation in disks, and synthetic mm continuum images clearly reveal these gaps and rings (Figure 12), resembling the morphology of the newly released ALMA image of HL Tau.

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APPENDIX

SEDs at viewing angles $\theta = 0^\circ$ and $45^\circ$ for Models $1 \times 0.2 M_J$, $1 \times 1 M_J$, $4 \times 1 M_J$, and $4 \times 2 M_J$ are shown in Figure 10. Models with multiple planets have less IR excess than models with a single planet at $\sim 10 – 100 \mu m$, and more emission at wavelengths beyond $\sim 100 \mu m$. This is because the gaps opened by multiple planets are bigger, resulting in lower emission from the gap region. Smaller gaps intercept less starlight, and therefore the outer disk receives more starlight resulting in higher grain temperature and more emission at long wavelengths. Nevertheless, the difference in the SEDs between models is marginal.

The raw images at $10 \mu m$ and $100 \mu m$ for Models $1 \times 0.2 M_J$, $1 \times 1 M_J$, $4 \times 1 M_J$, and $4 \times 2 M_J$ are shown in Figure 10 from viewing angles $\theta = 0^\circ$ and $45^\circ$. The images at $10 \mu m$ appear to be less empty comparing with at $100 \mu m$. Also, the dark lane at the mid-plane on the far (up) side of the gap wall is clearly visible at $10 \mu m$. Both features indicate that $10 \mu m$ images are mostly dominated by scattered light, while signals at $100 \mu m$ mainly come from dust thermal emission.

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TABLE 1

| Model name | Planet mass | Planet Position | Evolution Time |
|------------|-------------|-----------------|----------------|
| 1 × 0.2MJ  | 0.2         | 30.0            | 4 × 10^9       |
| 1 × 1MJ    | 1           | 30.0            | 4 × 10^5       |
| 4 × 1MJ    | 1/1/1/1     | 30.0/18.9/11.9/7.5 | 4 × 10^5 |
| 4 × 2MJ    | 2/2/2/2     | 30.0/18.9/11.9/7.5 | 4 × 10^5 |
| 3 × 0.2MJ  | 0.2/0.2/0.2 | 12/30/65        | 2 × 10^7       |

Note. — Properties of the hydro models.

TABLE 2

| Model | Grains     | Σ_{min,gap} | Σ_{max,out} | r_{max,out,Σ} | ζ_Σ  |
|-------|------------|-------------|-------------|--------------|------|
|       | g cm^{-2} | AU          |             |              |      |
| 1 × 0.2MJ | Small Grains | 3.0 × 10^{-3} | 4.0 × 10^{-3} | 40 | 1.3 |
|       | Big Grains  | 5.9 × 10^{-4} | 2.1         | 38           | 5300 |
| 1 × 1MJ  | Small Grains | 1.9 × 10^{-4} | 3.5 × 10^{-3} | 47 | 18  |
|       | Big Grains  | N/A         | 1.4         | 45 ≥ 10^9    |      |
| 4 × 1MJ  | Small Grains | 1.3 × 10^{-4} | 4.1 × 10^{-3} | 47 | 32  |
|       | Big Grains  | N/A         | 1.3         | 45 ≥ 10^9    |      |
| 4 × 2MJ  | Small Grains | 6.6 × 10^{-5} | 3.0 × 10^{-3} | 56 | 46  |
|       | Big Grains  | N/A         | 0.51        | 55 ≥ 10^9    |      |

Note. — Col. (1): Model name. Col. (2): Grain type. Col. (3): Minimum azimuthally averaged surface density inside the gap, not well defined in Σ_{bg} in models with M_p ≥ 1 MJ as Σ_{bg} reaches the hard floor set in hydro simulations. Col. (4): Maximum azimuthally averaged surface density in the outer disk. Col. (5): The location of Σ_{max,out}. Col. (6): Gap contrast ζ_Σ = Σ_{max,out}/Σ_{min,gap}; upper limits for the big grains in Models with M_p ≥ 1MJ.

TABLE 3

| Model | Band | r_{gap,in,image} | r_{gap,out,image} | Δ gap | r_{max,out,image} | I_{min,gap} | I_{max,out} | ζ_{image,conv} | ζ_{image,raw} | mJy arcsec^{-2} |
|-------|------|------------------|-------------------|-------|------------------|-------------|-------------|---------------|---------------|----------------|
|       |      | AU arcsec        | AU arcsec         | AU arcsec | AU arcsec | AU arcsec | AU arcsec | AU arcsec | AU arcsec | AU arcsec |
| 1 × 0.2MJ | H (PI) | N/A              | N/A               | N/A     | N/A     | 35        | 0.25       | 4.4          | 4.5          | 1.02           | 1.1        |
|       | ALMA B7 | 12 0.09           | 31 0.22           | 19 0.14 | 39 0.28  | 61        | 624        | 10           | 270          |                |
| 1 × 1MJ | H (PI) | 25 0.18           | 35 0.25           | 10 0.07 | 43 0.31  | 0.8       | 4.6        | 5.7          | 8.3          |                |
|       | ALMA B7 | N/A N/A           | N/A N/A           | N/A N/A | N/A N/A | 7.0       | 670        | 96           | 10^4         |                |
| 4 × 1MJ | H (PI) | 12 0.09           | 34 0.24           | 22 0.16 | 41 0.29  | 3.5       | 12.2       | 3.5          | 4.8          |                |
|       | ALMA B7 | N/A N/A           | N/A N/A           | N/A N/A | N/A N/A | 1.7       | 884        | 516          | 10^3.5       |                |
| 4 × 2MJ | H (PI) | 10 0.07           | 38 0.27           | 28 0.20 | 47 0.34  | 1.6       | 9.5        | 6.0          | 6.7          |                |
|       | ALMA B7 | N/A N/A           | N/A N/A           | N/A N/A | N/A N/A | 0.5       | 748        | 1593         | 10^3.5       |                |

Note. — Col. (1): Model name. Col. (2): Observational bands. H band is the polarized intensity. ALMA B7 is ALMA Band 7, continuum at 870 µm. Col. (3) and (4): Inner and outer gap edge in units of AU and arcsec (objects are at 140 pc from us), defined as the locations in the gap where the intensity reaches half of the peak value in the outer disk. For models with M_p ≥ 1MJ, thermal emission inside r_{gap,out,image} never reaches half of the peak intensity in the outer disk, so r_{gap,in,image} is not defined at ALMA B7. The NIR gap in Model 1 × 0.2MJ is too shallow to ever reach half of the peak density in the outer disk, so both gap edges are not defined. Col. (5): Peak intensity in the outer disk. Col. (6): Minimum intensity in the outer disk. Col. (7): Minimum intensity in the gap. Col. (8): Peak intensity in the outer disk. Col. (9): Gap contrast ζ_{image,conv} = I_{max,out}/I_{min,gap}. Col. (10): Similar to Col. (9), but for raw images. I_{min,gap} in raw images is chosen as a general floor value inside the gap, as the absolute minimum may be too low and is affected by the noise in MCRT simulations.
### Table 4
Comparison of NIR Gap Contrast between Observations and Models

| System Name     | Gap Contrast at $H$ Band | References                         |
|-----------------|--------------------------|------------------------------------|
| RX J1604.3-2130 | 3.6 ± 0.5                | Mayama et al. (2012)               |
| HD 142527       | 4.2 ± 1.2                | Canovas et al. (2013)              |
| SAO 206462      | 3.3 ± 1.9                | Garufi et al. (2013)               |
| PDS 70          | 3.5 ± 0.7 (along major axes) | Hashimoto et al. (2012)         |
| 4 × 1$M_J$      | 3.5                      | This work                          |
| 4 × 2$M_J$      | 6.0                      | This work                          |

**Note.** — The gap contrast in our models is the $c_{\text{image, conv}}$ defined in Table 3. The gap contrast in observed systems is measured in a similar manner, in which the value and the quoted error are the mean and standard deviation over different azimuthal angles. The first three observed systems are relatively face-on, while PDS 70 has a non-trivial inclination of 50°, so only major axes are taken into account. The floor intensity inside the gap is detected only in HD 142527. In the other three systems the possible inner edge of the gap (if exists) is blocked by the inner working angle in observations, so the measured gap contrast may be a lower limit. Observational noise is not added in our model images, so measured values may be upper limits. Nevertheless, the agreement between model results and observations is encouraging.
Fig. 1.— 2D surface density maps for the small (left column) and big grains (right column) from the hydro simulations (model names labeled on the left). The left column is also the scaled surface density distribution of the gas, as we assume that the small grains are well mixed with the gas, $\Sigma_{sg} = 0.1% \times \Sigma_g$. 
Fig. 2.— The azimuthally averaged surface density radial profile for both the small and big grains from the hydro models (model names labeled on the left). Note that the y-axis tick mark labels on the left are for the big grains and the ones on the right are for the small grains. The vertical black dash-dot lines indicate the position of the outermost planet in each model. The vertical blue and red dash-dot lines mark the positions of the peaks in $\Sigma_{sg}$ and $\Sigma_{bg}$ in the outer disk, respectively ($r_{\text{max, out, } \Sigma}$ in Table 3). The gap contrast (defined as the ratio of the peak surface density in the outer disk to the floor value inside the gap, $\zeta_{\Sigma}$ in Table 2) is about 1.5 orders of magnitude for the small grains in cases with $M_p \geq 1 M_J$, and $\sim 9$ orders of magnitude for the big grains. Note that $\Sigma_{bg}$ has a hard floor in the hydro simulations, so the gap contrasts for the big grains are lower limits.
Fig. 3.— 2D volume density map for the small (left) and big (right) grains showing the vertical structure ($r - \theta$ plane) at an azimuthal angle $\phi = 0^\circ$ in Model $1 \times 1 M_J$. The small dust disk is extended in the vertical direction and has a flared structure, while the big grains settle to the disk mid-plane due to aerodynamics effects. The gap around 30 AU is clearly visible in both grains.
Fig. 4.— Raw and convolved $H$ band polarized intensity images (left two columns) and ALMA band 7 (870 $\mu$m continuum) intensity images (right two columns) for our models (model names labeled on the left) at face on angle $\theta = 0^\circ$. Systems are assumed to be at 140 pc. The convolved images are convolved by a Gaussian kernel with FWHM=0.04$''$ at $H$ band and FWHM=0.1$''$ at ALMA band 7 (beam size indicated at the lower right corner in the convolved mm images) to mimic realistic angular resolutions. While models with four $M_p \geq 1M_\odot$ planets (the bottom two rows) all have a wide gap at both NIR and mm, in Model $1 \times 1M_\oplus$ (the second row) the NIR gap is much smaller than the mm gap. The NIR gap in Model $1 \times 0.2M_\oplus$ (the top row) may be too weak to be detectable, while the gap at mm wavelengths is significant.
Fig. 5.— Azimuthally averaged radial profiles of all images shown in Figure 4. The vertical black dash-dot lines indicate the position of the outermost planet in each model. The vertical blue and red dash-dot lines mark the positions of the peak intensity in the outer disk in the convolved H band and ALMA images, respectively ($r_{\text{max, out, image}}$ in Table 3). In all models, the peak intensity in the outer disk occurs at a larger disk radius at mm than at NIR (more prominent with more massive planets, as in Model $4 \times 2 M_J$). Also, NIR gaps are much shallower than mm gaps, in both raw and convolved images.
Fig. 6.— A zoomed-in version of the $H$ band images for Model $4 \times 2M_J$ in Figure 4 to highlight the density waves and the streamers inside the gap.
Fig. 7.— The same as Figure 4 but for viewing angle $\theta = 45^\circ$. 
Fig. 8.— Comparison of the $H$ band images at a viewing angle $\theta = 45^\circ$, between Model $4 \times 1 M_\odot$ (top row) and Model $4 \times 1 M_\odot$ with an empty cavity inside 35 AU (bottom row), as discussed in Section 3.3. The red dashed ellipses in the convolved images are fits to the bright ring in the images, and the red crosses mark the position of the star. The material inside the gap cast a shadow in the middle on the far (up) side of the outer gap wall in Model $4 \times 1 M_\odot$, while the entire outer gap wall is illuminated in Model $4 \times 1 M_\odot$-empty-gap. As a result of this geometric effect, the ring in the convolved image of Model $4 \times 1 M_\odot$ appears to be off-center, while in Model $4 \times 1 M_\odot$-empty-gap the ring is almost on-center.
Fig. 9.—A schematic flow chart showing how gap profiles in convolved images are converted from input planet+disk properties. First, observed images are raw images (with infinite resolution) convolved by the observational beams. For the raw images, the gap profile at NIR depends on the shape (curvature) of the disk surface, which is determined by the scale height and surface density of the small grains, which further depends on the masses and positions of the planets, and the disk viscosity and scale height. At sub-mm, it is set by the surface density and temperature of the big grains, which is further determined by the properties of the planets and the disk, dust-gas coupling effect, and the radiative transfer process in the disk.
Fig. 10.— Raw 10 μm intensity images (left two columns) and 100 μm intensity images (right two columns) for our models (model names labeled on the left) at viewing angles $\theta = 0^\circ$ and $45^\circ$. At 10 μm, gaps appear to be deeper than at 100 μm, and the shadow casted by the inner disk is visible on the outer gap wall in the inclined disk images.
Fig. 11.— SEDs for Models $1 \times 0.2M_\text{J}$, $1 \times 1M_\text{J}$, $4 \times 1M_\text{J}$, and $4 \times 2M_\text{J}$ at a viewing angle $\theta = 45^\circ$. The difference between models is marginal.
Fig. 12.— Model $3 \times 0.2 M_J$: A $0.17 M_J$ disk with $3 \times 0.2 M_J$ planets located at 12, 30, and 65 AU 0.2 Myr after their formation, showing multiple gaps well separated by rings. Top: 2D surface density map for the small (left) and big (right) grains. The left panel is also the scaled surface density distribution of the gas, as we assume that the small grains are well mixed with the gas, $\Sigma_{sg} = 0.1% \times \Sigma_g$. Bottom: Raw and convolved $H$ band polarized intensity images (left two columns) and ALMA band 7 (870 $\mu$m continuum) intensity images (right two columns) at face on (top row) and an inclined angle $\theta = 45^\circ$ (bottom row). Systems are assumed to be at 140 pc. The convolved images are convolved by a Gaussian kernel with FWHM=0.04$''$ at $H$ band and FWHM=0.035$''$ at ALMA band 7 (beam size indicated at the lower right corner in the convolved mm images). The three planets in this case each opens a narrow gap in both the small and big grains. While signals of the gaps in the convolved NIR images are relatively weak, three narrow gaps well separated by bright rings are clearly visible at mm wavelengths at both inclinations. See Section 4.2 for detailed discussion.
Fig. 13.— Radial profiles of the 2D images in Figure 12. Top: The azimuthally averaged surface density radial profile for both the small and big grains from the hydro models. Note that the y-axis tick mark labels on the left are for the big grains and the ones on the right are for the small grains. Bottom: Azimuthally averaged radial profiles of all images shown in Figure 4. The vertical black dash-dot lines indicate the positions of the three planets in both panels.