Observations of Circumplanetary Disks with ngVLA

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Abstract

Planets are formed in protoplanetary disks and gas giant planets are surrounded by circumplanetary disks (CPDs), which are the birth place of moons. Candidate CPDs have been reported at infrared wavelength, and more recently at millimeter wavelength by ALMA. Model calculations suggest that ngVLA will be able to detect dust continuum emission from CPDs at wavelength of 3 mm. In addition, CO $J = 1 - 0$ line will be detectable if CPDs are bright enough. Detection of dust continuum emission at ngVLA Bands together with ALMA Bands will make constraint on the properties of dust grains: temperature, optical depth and frequency dependence of opacity, which will be useful to understand the moon formation in the CPDs.

Key words: circumplanetary disks — dust grains — satellite formation

1. Introduction

Planets are formed in protoplanetary disks, and gas giant planets are surrounded by circumplanetary disks (CPDs) when they are formed, according to the results of hydrodynamical simulations (e.g., Lubow et al. 1999; Machida et al. 2010; Tanigawa et al. 2012). In the CPDs, regular moons, such as the Galilean moons of Jupiter in our Solar system, are expected to be formed. It is known from observations of the Galilean moons that compositions of moons, such as ice mass fractions, are very different, depending on the distance from the central planets, and they will be controlled by the physical conditions of the CPDs (e.g., Canup & Ward 2002; Canup & Ward 2006; Shibaike et al. 2019).

Formation processes of CPDs and moons are theoretically well studied, but these theories are hardly tested by observations. Candidate CPDs of infrared point sources have been reported so far (e.g., Sallum et al. 2015; Müller et al. 2018). Meanwhile, Atacama Large Millimeter/submillimeter Array (ALMA) has now revealed that most of the spatially resolved protoplanetary disks have ring and gap structures in their dust continuum images, which are often linked with the structures caused by gravitational interaction with planets formed in the disks (e.g., Fig. 1, ALMA Partnership et al. 2015; Andrews et al. 2016; Tsukagoshi et al. 2016; Andrews et al. 2018). However, since the ring and gap structures can be formed not only by planets, but also by other mechanisms, such as dust accumulation near the snowlines of molecules (e.g., Zhang et al. 2015; Okuzumi et al. 2016), more direct evidences are required for further understanding of planet and CPD formation in the protoplanetary disks. More recently, high spatial resolution and high sensitivity observations by ALMA have succeeded to detect au-scale millimeter point sources in dust continuum emission from protoplanetary disks, which are candidates of CPDs (Fig. 1, Tsukagoshi et al. 2019; Isella et al. 2019).

Observations of CPDs with ngVLA are useful to make constraint on the properties of dust grains in CPDs, together with the multiwavelength observations by ALMA. In addition, the CO $J = 1 - 0$ line will be detectable from CPDs with ngVLA if the disks are bright enough. These observations will be helpful to understand the formation process of moons in CPDs.

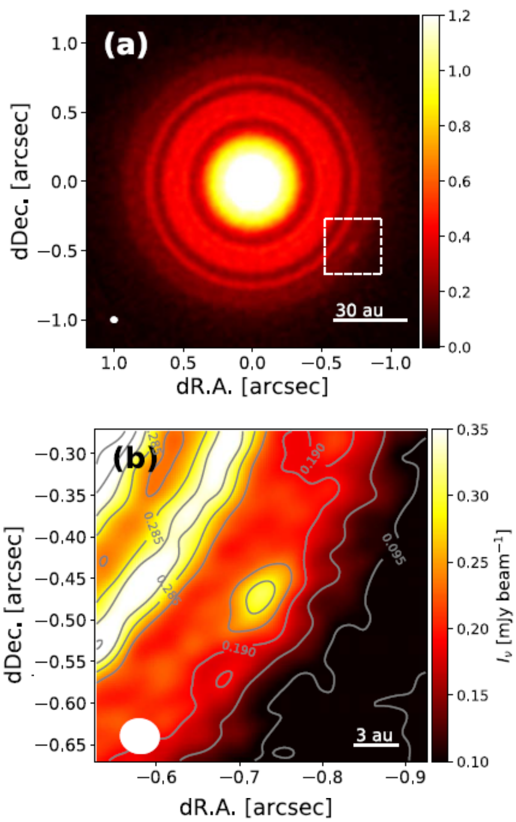

Fig. 1. ALMA observations of a planet forming disk with a signature of a circumplanetary disk (Tsukagoshi et al. 2019).

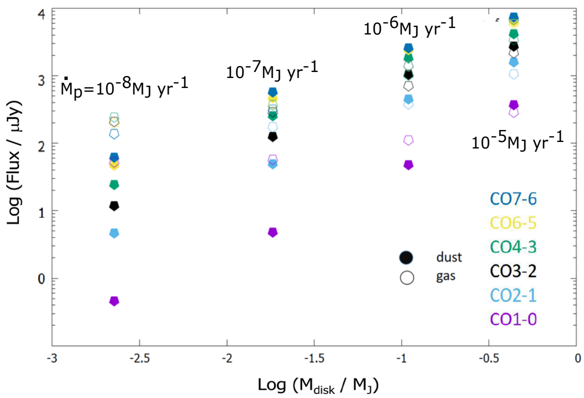

Fig. 2. Model prediction for fluxes of dust continuum emission and fluxes at line peaks of CO transition lines from CPDs with various mass accretion rates as a function of disk mass.

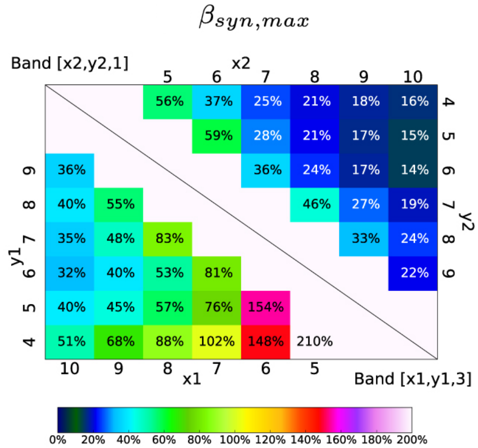

Fig. 3. Deviation of frequency-dependent dust opacity power-law index, β, obtained by synthesized multi-wavelength observations from the model value. The ngVLA Band 6 (= ALMA Band 1) is included for the results in the top-right, while only ALMA Bands 3-10 are used for the results in the bottom-left. (See Kim et al. 2019 for details).

2. Detectability of Dust and Gas Emission from Circumplanetary Disks

Fluxes of dust continuum emission and CO line emission from CPDs are calculated based on the viscous accretion disk model in Zhu et al. (2018) (see also Shakura & Sunyaev 1973). A planet with Jupiter mass and Jupiter radius is used in the model. The mass accretion rates of $\dot{M}_p = 10^{-8} - 10^{-5} M_J \mathrm{yr}^{-1}$, the turbulent viscous parameter of $\alpha = 0.001$, and the outer disk radius of 3 au are adopted for the CPD model. Fig. 2 shows the calculated fluxes of CO $J = 7-6, 6-5, 4-3, 3-2, 2-1$ and $1-0$ lines and dust continuum emission at the corresponding wavelengths as a function of the disk mass (see also Rab et al. 2019). The CO $J = 1-0$ line and the dust continuum emission at the corresponding wavelength is observable at ngVLA Band 6. If the CPD is located at a distance of 150 pc from the Earth, the angular size of the disk diameter is 40 mas. The dust continuum emission is optically thin and the fluxes are proportional to the disk mass. For the model with $\dot{M}_p = 10^{-7} M_J \mathrm{yr}^{-1}$, the dust continuum emission from an unresolved disk is detectable with $\sim 8\sigma$ level with $\sim$ 1hr integration time. If we resolve it with a beam size of 20 mas, $\sim$ 5hr integration time is needed in order to detect it with $\sim 5\sigma$ level. For the model with $\dot{M}_p = 10^{-8} M_J \mathrm{yr}^{-1}$, we need more than 25 hr for $\sim 5\sigma$ detection. The CO $1-0$ line is optically thick and the line flux is not sensitive to the disk mass, but affected by the disk temperature. The detection of the line emission is relatively difficult and requires $\sim$ 5hr integration time even in the case of the model with $\dot{M}_p = 10^{-5} M_J \mathrm{yr}^{-1}$. Such high accretion rate could be achieved according to episodic mass accretion scenario of CPDs (Brittain et al. 2020).

3. Dust Properties Constrained by Multi-Wavelength Observations

Detection of dust continuum emission at the ngVLA Bands is useful for constraining the properties of dust grains in the CPDs. Multi-wavelength observations of dust continuum emission, including both optically thin and thick wavelengths, give information of dust temperature, dust optical depth, and frequency dependence of dust opacity ($\kappa \propto \nu^{\beta}$, ν is the frequency). Observations of dust continuum emission at ngVLA Bands together with ALMA Bands give a wider wavelength range, and thus, better constraint on the dust properties. Fig. 3 shows that if we include ngVLA Bands for the multi-wavelength observations, the constraint on β becomes better by roughly three times than those with ALMA Bands 3-10 only for a certain model (Kim et al. 2019). Since moons will be formed as a result of dust growth, the obtained dust properties will be useful to understand the moon formation in the CPDs.

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