An Explanation of the Very Low Radio Flux of Young Planet-mass Companions

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Abstract

We report Atacama Large Millimeter/submillimeter Array (ALMA) 1.3 mm continuum upper limits for five planetary-mass companions DH Tau B, CT Cha B, GSC 6214-210 B, IRX 1609 B, and GQ Lup B. Our survey, together with other ALMA studies, have yielded null results for disks around young planet-mass companions and placed stringent dust mass upper limits, typically less than 0.1 M☉, when assuming dust continuum is optically thin. Such low-mass gas/dust content can lead to a disk lifetime estimate (from accretion rates) much shorter than the age of the system. To alleviate this timescale discrepancy, we suggest that disks around wide companions might be very compact and optically thick in order to sustain a few Myr of accretion, yet have very weak (sub)millimeter flux so as to still be elusive to ALMA. Our order-of-magnitude estimate shows that compact optically thick disks might be smaller than 1000 RJuP, and only emit ~μJy of flux in the (sub)millimeter, but their average temperature can be higher than that of circumstellar disks. The high disk temperature could impede satellite formation, but it also suggests that mid- to far-infrared might be more favorable than radio wavelengths to characterize disk properties. Finally, the compact disk size might imply that dynamical encounters between the companion and the star, or any other scatterers in the system, play a role in the formation of planetary-mass companions.

Key words: accretion, accretion disks – planets and satellites: general – techniques: interferometric

1. Introduction

Direct imaging of circumplanetary disks is crucial to study how planets and their satellites actually form. Theoretical modeling has suggested that circumplanetary disks can emit significant infrared fluxes, and magnetospheric accretion on the surface of protoplanets can create strong line emission and UV/optical continuum excess (e.g., Eisner 2015; Zhu 2015; Zhu et al. 2016). Recently, high-contrast imaging campaigns have been targeting transition disks to search for these accretion signatures inside the central holes or gaps. While a few red sources have been identified as protoplanet candidates, their nature remains elusive and some may actually be disk features or data reduction artifacts (e.g., Biller et al. 2014; Sallum et al. 2015a; Follette et al. 2017). So far, the only confirmed accreting planet is LkCa 15 b, which emits at Hα (Sallum et al. 2015b), but its accretion disk has yet to be directly resolved (Isella et al. 2014).

One can also search for disks around wide-orbit planetary-mass companions, which are ~5–40 MJup gas giants orbiting at tens to hundreds of astronomical units. Wide companions, unlike the copious transiting planets, are intrinsically rare tens to hundreds of astronomical units. Wide companions, unlike the copious transiting planets, are intrinsically rare (e.g., Nielsen & Close 2010), so their formation scenario may not resemble that of planets (i.e., core accretion) but more like brown dwarfs or low-mass stars (e.g., Brandt et al. 2014). Nonetheless, their wide separations offer a direct view into the physical mechanisms that can regulate planet formation in circumplanetary disks. Analytic and numerical analyses have shown that circumplanetary disks are truncated at approximately one-third of the planet’s Hill radius (e.g., Quillen & Trilling 1998; Ayliffe & Bate 2009). Shabram & Boley (2013) further demonstrated that gas giants formed via disk fragmentation at 100 au can harbor such a truncated disk. Simulations have predicted that circumplanetary disks are luminous at radio wavelengths and may be easily detectable by the Atacama Large Millimeter/submillimeter Array (ALMA; e.g., Shabram & Boley 2013; Zhu et al. 2016).

Recently, there have been several attempts to search for accretion disks around wide companions with radio interferometers such as the NOrthern Extended Millimeter Array and ALMA (Bowler et al. 2015; MacGregor et al. 2017; Ricci et al. 2017; Wolff et al. 2017; Wu et al. 2017). None of these studies has successfully detected a wide companion disk. In Table 1 and Figure 1, we show our ALMA 1.3 mm survey for five systems, GQ Lup,3 CT Cha, DH Tau, GSC 6214-210, and IRX 1609. Data have been self-calibrated and CLEANed with natural weighting. Details on the observational setup and data reduction can be found in Wu et al. (2017) and Wu & Sheehan (2017). As with other studies, no companions are detected in our survey. We note that a disk has been detected around the proposed planet-mass companion FW Tau C (Kraus et al. 2014, 2015; Caceres et al. 2015), but a recent dynamical mass measurement has shown that FW Tau C is a ~0.1 M☉ star (Wu & Sheehan 2017).

2. Optically Thin Dust and Timescale Problem

Assuming optically thin dust, one can estimate the dust mass from Hildebrand (1983),

\[ M_{\text{dust}} = \frac{F_{\nu} D^2}{\kappa_\nu B_{\nu}(T)} \]

where \( F_{\nu} \) is the observed flux, \( D \) is the distance to the source, \( \kappa_\nu \) is the dust opacity, and \( B_{\nu}(T) \) is the Planck function. In Table 2, we list the physical properties, disk evidence, 3σ radio flux limits (from our observations and the literature), and the corresponding dust mass limits for five planetary-mass companions.

\[ M_{\text{dust}} \]

The GQ Lup data have been published in Wu et al. (2017), and we include them here for completeness.
companions in our survey. We notice that the ~5 M_Jup planet 2M1207 b has a 880 μm flux limit of ~80 μJy recently measured by Ricci et al. (2017). Hence, current ALMA observations have reached 3σ sensitivities of 80–220 μJy at 880 μm and 90–150 μJy at 1.3 mm for wide companions. These flux upper limits translate to a dust mass of 0.002–0.14 M_⊕ (0.2–11.4 M_moon) assuming a characteristic disk temperature of 20 K. Because many wide companions have multiple features suggestive of accretion disks, it is surprising and puzzling that radio observations have placed such a strong constraint on the amount of dust. The small amount of dust in turn implies a very short disk lifetime due to accretion. For instance, GQ Lup B has an accretion rate of 5 × 10^{-7} M_Jup yr^{-1} (Zhou et al. 2014), yet an optically thin disk has <0.04 M_⊕ of dust (MacGregor et al. 2017). Hence, GQ Lup B’s accretion disk could potentially disappear in ~20 kyr, much shorter than the 2–5 Myr age of the system. If the actual gas-to-dust ratio is lower than the canonical value of

| Source        | Date       | N_{ant} | L_{baseline} (m) | T_{obs} (min) | Gain Cal. | Flux Cal. | Bandpass Cal. | Beam (″) | PA (°) | rms (μJy beam^{-1}) |
|---------------|------------|---------|------------------|--------------|-----------|-----------|---------------|---------|-------|-------------------|
| GQ Lup        | 2015 Nov 01| 41      | 85–14969         | ~11          | J1534–3526| J1337–1257| J1427–4206   | 0.054 × 0.031| 68.7  | ~40               |
| DH Tau        | 2016 Sep 14| 36      | 15–3247          | ~13          | J0433–2905| J0510–1800| J0510+1800   | 0.286 × 0.153| ~19.8 | ~43               |
| GSC 6214-210  | 2016 Sep 16| 36      | 15–3143          | ~12          | J1634–2058| J1517–2422| J1517–2422   | 0.202 × 0.172| ~2.3  | ~30               |
| 1RXS 1609     | 2016 Sep 16| 36      | 15–3143          | ~12          | J1634–2058| J1517–2422| J1517–2422   | 0.202 × 0.176| ~1.5  | ~30               |
| CT Cha        | 2016 Sep 27| 36      | 15–3247          | ~14          | J1058–8003| J1107–4449| J1107–4449   | 0.259 × 0.134| 16.5  | ~50               |

Figure 1. A gallery of ALMA 1.3 mm non-detections. The 3σ flux limits range from 90 to 150 μJy, corresponding to 0.06 to 0.14 M_⊕ of dust under optically thin approximation. North is up and east is left for all panels. We detect circumstellar disks around GQ Lup A, CT Cha A, and DH Tau A, with fluxes of ~27, ~35, and ~33 mJy and disk radii of ~20, ~41, and ~16 au, respectively. The GQ Lup A and CT Cha A disks are spatially resolved, while the DH Tau A disk is marginally resolved. Full analysis of the GQ Lup A disk is reported in Wu et al. (2017), and disk modeling for CT Cha A and DH Tau A will be presented in a future paper.
Table 2
Planet-mass Companions in Wide Orbits

|                | GQ Lup B | DH Tau B | GSC 6214-210 B | 1RXS 1609 B | CT Cha B |
|----------------|----------|----------|----------------|-------------|----------|
| Mass ($M_{\text{Jup}}$) | ~10–40   | ~15      | ~15            | ~13         | ~20      |
| SpT            | L1 ± 1   | M9.25 ± 0.25 | M9.5 ± 1      | L2 ± 1     | M8       |
| log($L/L_\odot$) | −2.47 ± 0.28 | −2.71 ± 0.12 | −3.1 ± 0.1    | −3.36 ± 0.09 | −2.66 ± 0.21 |
| $T_{\text{eff}}$ (K) | 2400 ± 100 | 2400 ± 100 | 2200 ± 100 | 2000 ± 100 | 2600 ± 100 |
| Age (Myr)      | 2–5      | ~2       | ~10           | ~10        | ~2       |
| $D$ (pc)       | ~150     | ~140     | ~150          | ~150       | ~180     |
| $\rho$ ($''$)  | 0.72     | 2.35     | 2.17          | 2.21       | 2.68     |

Accretion and disk markers:
- H$_\alpha$, Pa-β
- red $K'$–$L'$
- H$_\alpha$, Pa-β, Br-γ
- red $K'$–$L'$
- high $A_V$
- Pa-β
- high $A_V$

$M$ ($M_{\text{Jup}}$ yr$^{-1}$): 5.3 × 10$^{-7}$, 4.2 × 10$^{-9}$, 1.3 × 10$^{-8}$, ... , ... 3σ Flux Limit ($\mu$Jy): 150 (880 $\mu$m), 130 (1.3 mm), 220 (880 $\mu$m), 90 (1.3 mm), 150 (1.3 mm)

3σ Dust Limit$^b$ ($M_\odot$): <0.04, <0.07, <0.05, <0.06, <0.14

References: (1) Wu et al. (2017) and references therein, (2) MacGregor et al. (2017), (3) Zhou et al. (2014), (4) Kraus et al. (2014), (5) Bonnefoy et al. (2014) and references therein, (6) Wolff et al. (2017), (7) Bailey et al. (2013) and references therein, (8) Bowler et al. (2014), (9) Bowler et al. (2015), (10) Wu et al. (2015b) and references therein, (11) Wu et al. (2015a) and references therein, (12) Voirin et al. (2017).

Figure 2. Disk flux as a function of disk radius for 1000 and 2500 K companions under the optically thick approximation. ALMA 880 $\mu$m and 1.3 mm flux limits suggest that compact optically thick disks are probably smaller than 1000 $R_{\text{Jup}}$, or ~0.5 au.

100, as hinted by recent ALMA surveys on T Tauri disks (e.g., Ansdell et al. 2016; Eisner et al. 2016), then GQ Lup B’s disk would be depleted even faster.

This dramatic timescale difference seems to suggest that we are observing planet-mass companions at a very special time close to the very end of accretion, which is a priori unlikely. We note that at an age of ~10 Myr, GSC 6214-210 B still has lines of evidence arguing for active accretion (see Table 2). This implies that disks around planet-mass companions can indeed survive for a long period, presumably longer than the average lifetime of protoplanetary disks (~5 Myr; Haisch et al. 2001).

3. Compact Optically Thick Disk

Low radio flux does not necessarily mean low dust mass. A more natural explanation is that their disks may have the mass needed to sustain accretion and satellite formation for a few to
even $>10$ Myr ($>0.1 M_{\text{Jup}}$ or even $>1 M_{\text{Jup}}$), but they appear faint in (sub)millimeter because the disks are compact. This is also hinted by infrared observations, as some companions have near- or mid-infrared excesses likely from hot inner disks (Table 2), implying that the lack of (sub)millimeter detections requires small disk radii.

Compact dust continuum emission is optically thick, rather than optically thin as usually assumed. We note that similar thoughts have been discussed and applied to derive an upper limit on disk size (Bowler et al. 2015; MacGregor et al. 2017; Ricci et al. 2017; Wolff et al. 2017). Here, we further study the brightness and implications of compact optically thick disks.

Assuming disk heating is dominated by the irradiation from the companion, we can roughly estimate the brightness of an optically thick disk following Pringle (1981). The temperature profile is

$$T(r) = T_* \left(\frac{r}{R_*}\right)^{-3/4} \left(1 - \sqrt{\frac{R_*}{r}}\right)^{1/4},$$  \hspace{1cm} (2)

where $T_*$ and $R_*$ are the effective temperature and radius of the central object, respectively. For $r \gg R_*$, $T(r) \propto r^{-3/4}$, which is similar to the profile seen in some simulated circumplanetary disks (e.g., Ayliffe & Bate 2009). We can calculate the disk flux $F_\nu$ by integrating the Planck function $B_\nu$ over solid angle:

$$F_\nu = \int B_\nu(T(r)) d\Omega = \frac{2\pi}{D^2} \int_{R_{\text{min}}}^{R_{\text{max}}} B_\nu(T(r)) r \, dr,$$  \hspace{1cm} (3)

where $R_{\text{min}}$ and $R_{\text{max}}$ are the disk inner and outer radii, respectively. At long wavelengths, $B_\nu \propto T$, so $F_\nu$ approximately scales as $R_{\text{max}}$.

We adopt $R_* = 2.5 R_{\text{Jup}}$, which is typical for young substellar objects (e.g., Baraffe et al. 2015), $R_{\text{min}} = 2 R_*$, $R_{\text{max}} = 10^{-4} R_{\text{Jup}}$ ($\sim 0.005$–$0.5$ au), and $D = 150$ pc as most nearby star-forming regions are approximately at that distance.

Finally, we choose $T_* = 2500$ and $1000$ K, as most companions have spectral types from late M to mid L (Table 2). Figure 2 shows the disk radius versus the $880 \mu$m (ALMA band 7) and $1.3$ mm (ALMA band 6) disk fluxes given by Equation (3). We also label the $3\sigma$ flux upper limits from ALMA observations. We can see that compact optically thick disks are indeed very faint at radio wavelengths—current observational constraints suggest that they are fainter than $\sim 100 \mu$Jy. As a result, they cannot be as large as one-third of the Hill radius ($\sim 5$–$30$ au in radius), or we would have easily detected them with ALMA. Instead, Figure 2 suggests that they are probably smaller than $1000 R_{\text{Jup}}$, or $\sim 0.5$ au. Such small optically thick disks can still contain all of the gas and dust needed for a few Myr of steady accretion onto the companion, hence solving the lifetime problem created by the ALMA non-detections.

4. Implications

If these planet-mass companions do indeed have compact optically thick disks, then our calculations have a few implications, as follows.

1. ALMA may not be the ideal instrument to detect and characterize circumplanetary disks. As Figure 2 shows, disk flux roughly scales with disk size, so detecting a disk that is 10 times smaller in size would require $\sim 100$ times longer integration to reach the same signal-to-noise ratio. Therefore, an unrealistically long integration is required for ALMA to reach an rms of $1 \mu$Jy in order to detect disks smaller than $1000 R_{\text{Jup}}$.

2. Mid-infrared observations, which probe the peak of the spectral energy distribution (SED) of compact disks, may be more favorable for constraining disk sizes in order to compare with theories. The average temperature of compact optically thick disks can be higher...
than that of T Tauri disks (~25 K; e.g., Andrews et al. 2013). The area-weighted disk temperatures, $T_{\text{disk}} = \int_{R_{\text{min}}}^{R_{\text{max}}} T(r)2\pi r \, dr / (\pi R_{\text{max}}^2 - \pi R_{\text{min}}^2)$, for disk radii of $10^5$–$1000 R_{\text{Jup}}$ (~0.005–0.5 au) range from ~40 K to ~880 K for a 2500 K companion, and ~20 K to ~350 K for a 1000 K companion. As a result, compact disks are bright in the mid- to far-infrared. Figure 3 shows the SEDs derived from Equation (3) for 10, 100, and $1000 R_{\text{Jup}}$ compact disks. It is evident that the peak of SED is size-dependent, ranging from ~10 to ~100 $\mu$m. We also plot the $3\sigma$ point source detection limits for 1000 s integration time for the Mid-Infrared Instrument (MIRI) on the James Webb Space Telescope. MIRI’s superior sensitivity at 10–25 $\mu$m will be able to constrain disk sizes for most young planetary-mass companions.

3. The origin of planetary-mass companions requires further exploration. Non-detections of wide companion disks are in stark contrast to recent studies, which reveal that planet-mass companions share similar masses to free-flying planets, they probably have a different formation pathway that involves dynamical encounters with other massive bodies to truncate their disks and also scatter them to outer orbits (e.g., Bate et al. 2003). However, searches for inner massive bodies that can serve as the scatterers seem to disagree with the scattering scenario but favor the in situ formation via disk fragmentation or prestellar core collapse (Bryan et al. 2016).

4. Moons could be hard to form in compact optically thick disks in the first few Myr because of the high disk temperature. In the inner disk, the temperature can be even higher than the dust sublimation temperature. As a result, satellite formation might have to wait until the companion cools off, or only occur in the outer disk where the temperature is lower (e.g., Zhu et al. 2016; Szulágyi 2017).

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