

MASSIVE PROTOPLANETARY DISKS IN ORION BEYOND THE TRAPEZIUM CLUSTER

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ABSTRACT

We present Submillimeter Array¹ observations of the 880 μm continuum emission from three circumstellar disks around young stars in Orion that lie several arcminutes ($\gtrsim 1$ pc) north of the Trapezium cluster. Two of the three disks are in the binary system 253-1536. Silhouette disks 216-0939 and 253-1536a are found to be more massive than any previously observed Orion disks, with dust masses derived from their submillimeter emission of $0.045 M_{\odot}$ and $0.066 M_{\odot}$, respectively. The existence of these massive disks reveals that the disk mass distribution in Orion does extend to high masses, and that the truncation observed in the central Trapezium cluster is a result of photoevaporation due to the proximity of O-stars. 253-1536b has a disk mass of $0.018 M_{\odot}$, making the 253-1536 system the first optical binary in which each protoplanetary disk is massive enough to potentially form solar systems.

Key words: circumstellar matter – planetary systems: protoplanetary disks – solar system: formation – stars: pre-main sequence

1. INTRODUCTION

The formation of planetary systems is intimately connected to the properties of the circumstellar disks in which they are born. Most studies to date have focused on young disks in Taurus-Auriga and ρ Ophiuchus for their proximity. However, most stars do not form in relative isolation as in Taurus and ρ Ophiuchus, but rather in dense, massive star clusters that produce ionizing radiation (Lada & Lada 2003), which threatens the persistence of nearby circumstellar disks (Johnstone et al. 1998). There is even clear evidence based on the presence of short-lived radionuclides, particularly ^{60}Fe , in meteorites (Tachibana et al. 2006), which indicate our own Solar System originated in a massive star-forming environment (Krot et al. 2005; Gaidos et al. 2009).

Orion is the nearest young massive star-forming region, and its favorable geometry due to a “blister H II” region aligned toward the Sun has allowed over 200 young protoplanetary disks (“proplyds”) to be discovered in projection against the bright background nebula by the *Hubble Space Telescope* (HST; O’Dell & Wen 1994; O’Dell & Wong 1996; Bally et al. 1998a, 2000; Ricci et al. 2008). The potential for the proplyds to form planetary systems depends on how much mass remains in the disks, in spite of the hostile environment. Several millimeter interferometric surveys have been undertaken to determine the masses of these disks, but few proplyds were detected in excess of the ionized gas emission, which swamps the dust emission at centimeter to millimeter wavelengths (Mundy et al. 1995; Bally et al. 1998b; Eisner & Carpenter 2006; Eisner et al. 2008). With its higher frequency observations, the Submillimeter Array (SMA) is more sensitive to dust-disk emission from the Orion proplyds than any existing interferometer (Williams et al. 2005).

The initial results of our SMA survey of disk masses in the Orion Trapezium cluster revealed this region is missing the most massive disks found in Taurus and ρ Ophiuchus, most likely a result of photoevaporation by the most massive star of the cluster, θ^1 Ori C (Mann & Williams 2009, hereafter Paper I). Photoevaporation rapidly erodes large and massive disks near

O-stars, but at larger distances, the flux of ionizing radiation drops significantly and no longer influences the disks. Using our observations, we searched for a disk mass dependence on distance from θ^1 Ori C, but did not find one. In order to explore the extent of the disk mass truncation in Orion, we imaged two HST-identified proplyds at larger distances from the Trapezium cluster.

In this Letter, we present our submillimeter observations of two HST-identified disks, 216-0939 and 253-1536,² located in the outskirts of the Orion Nebula (see Figure 1). These disks are seen in silhouette and were discovered by Smith et al. (2005). Proplyd 216-0939 is a 2.6 flared disk surrounding a $0.69 M_{\odot}$ star (Hillenbrand 1997), while proplyd 253-1536 is a suspected binary system (Nielbock et al. 2003; Smith et al. 2005; Köhler et al. 2006; Reipurth et al. 2007), with a disk surrounding the apparently fainter companion. Both disks lie many arcminutes ($\gtrsim 1$ pc) north of the Trapezium cluster (see Figure 1), well away from the ionizing radiation of θ^1 Ori C. The SMA observations are described in Section 2, followed by our determination of disk masses in Section 3. We discuss the implications of our observations for planet formation in Orion in Section 4.

2. OBSERVATIONS

Submillimeter interferometric observations at 880 μm were conducted with the SMA in its compact configuration on 2008 December 23 and 2008 December 24 on Mauna Kea toward disks 216-0939 and 253-1536. In this arrangement, the SMA’s eight 6 m antennas provide a maximum baseline of 70 m. Additional observations of 253-1536 were obtained on 2009 March 26 and 27 using the very extended (VEX) configuration, which provides baselines up to 508 m. Double sideband receivers were tuned to an intermediate frequency (IF) of 340.175 GHz. Each sideband provides 2 GHz of bandwidth, separated by ± 5 GHz from the IF. We simultaneously observed the CO(3–2) transition, which was strongly detected but maps show that any line emission from the disk is substantially contaminated by confusion with the more extended molecular cloud background. Weather conditions for the observations were good, with < 3 mm precipitable water vapor, resulting in system temperatures ranging from 100 to 400 K.

¹ The Submillimeter Array is a joint project between the Submillimeter Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.

² Proplyd designation based on the nomenclature of O’Dell & Wen (1994).

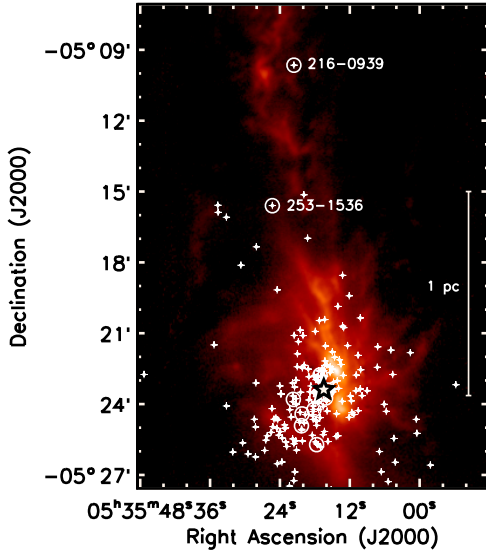


Figure 1. Large-scale view of the Orion Nebula at $450\ \mu\text{m}$. Imaging was done using SCUBA on the 15 m James Clerk Maxwell Telescope (Johnstone & Bally 1999). The crosses mark the location of *HST*-identified proplyds, and the star shows the position of θ^1 Ori C, the most massive star of the Trapezium cluster. The solid circles represent the $32''$ primary beam of each SMA field. The massive disks, 216-0939 and 253-1536, are clearly marked with their location.

The raw visibilities for each night were calibrated and edited using the MIR software package. The phase and amplitudes were monitored with 5 minute integrations of two quasars (J0423–013 and J0530+135), which were interleaved with 20 minute on-source integrations. Passband calibration was conducted with the bright quasar 3c273 and Uranus was used to set the absolute flux scale, which is accurate to $\sim 10\%$. The calibrated visibilities were weighted by system temperature and inverted, then deconvolved to generate continuum maps using the MIRIAD software package.

CO(3–2) was edited out of the $880\ \mu\text{m}$ observations to generate a line-free continuum, which was used to produce the final maps shown in Figure 2. Images were created for uv -spacings greater than $27\ \text{k}\lambda$, or physical baselines longer than $23\ \text{m}$, to filter out uniform extended emission greater than $7''.5$ in size, larger than resolved *HST* disk sizes.

The map of 216-0939 was made with only compact array observations, so longer baseline data were weighted higher (super-uniform weighting) in order to maximize the resolution to get a circular $1''.4 \times 1''.4$ beam. The map of 253-1536 combined the compact and VEX SMA observations. The addition of VEX observations to the compact configuration data significantly improved the beam size from $1''.5 \times 1''.4$ to $0''.3 \times 0''.2$. The improvement in resolution allowed us to resolve and distinguish disk emission from each source in the binary, and we label the primary and secondary disks 253-1536a and 253-1536b, respectively.

3. RESULTS

Figure 2 shows the $880\ \mu\text{m}$ continuum images of proplyds 216-0939 and 253-1536 alongside their discovery *HST* $\text{H}\alpha$ images taken from Smith et al. (2005). All three disks were very strongly detected, and their integrated flux densities are listed in Table 1.

As the silhouette disks show no signs of being photoevaporated, the free-free emission from ionized gas emission is not expected to be significant. The disks lie in regions where the

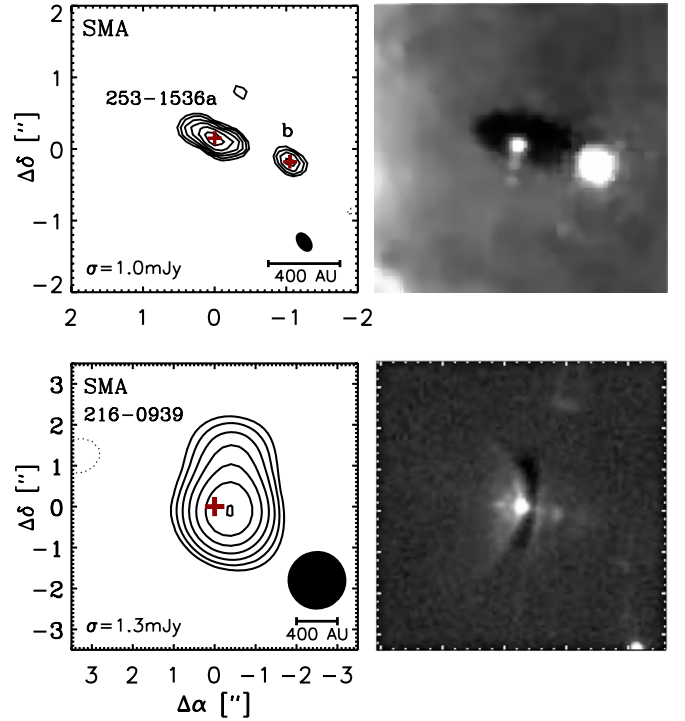


Figure 2. SMA images of the $880\ \mu\text{m}$ continuum emission from Orion disks 216-0939 and 253-1536a, 253-1536b. *HST* $\text{H}\alpha$ discovery images were taken directly from Smith et al. (2005) and are also shown using the same field of view: $7'' \times 7''$ for 216-0939 and $4'' \times 4''$ for 253-1536a and b. Contours begin at the 5σ level, where σ is the rms noise level in the map, and is specified in the lower left corner. Each step represents a factor of 1.5 in intensity. The synthesized beam size is shown in the lower right corner of each map.

molecular cloud emission is lower and more uniform than for the central Trapezium cluster surveyed in Paper I. Bolometer maps made with the SCUBA camera on the James Clerk Maxwell Telescope by Johnstone & Bally (1999) were used to correct background emission in a similar way to Paper I. The background was found to contribute $< |1\ \text{mJy}|$ to the disk fluxes, much less than calibration errors. Therefore, since both the ionized gas and background molecular cloud emission are negligible, the $880\ \mu\text{m}$ fluxes arise entirely from the dust-disks and unlike Paper I, we do not make any corrections.

The disk masses were derived from the dust fluxes using the standard relationship from (Beckwith et al. 1990):

$$M_{\text{disk}} = \frac{F_{\text{dust}} d^2}{\kappa_{\nu} B_{\nu}(T)}, \quad (1)$$

where $d = 400\ \text{pc}$ is the distance to Orion (Sandstrom et al. 2007; Menten et al. 2007), $\kappa_{\nu} = 0.1(\nu/1000\ \text{GHz}) = 0.034\ \text{cm}^2\ \text{g}^{-1}$ is the dust grain opacity with an implicit gas-to-dust mass ratio of 100:1, and $B_{\nu}(T)$ is the Planck function. A dust temperature of $T = 20\ \text{K}$ was used, which is the average for disks in Taurus-Auriga and ρ Ophiuchus (Andrews & Williams 2005, 2007). We used the same temperature and opacity as these disk surveys and also of Orion (Mann & Williams 2009) for consistency.

The resulting disk masses are $0.045\ M_{\odot}$ for proplyd 216-0939, $0.066\ M_{\odot}$ for 253-1536a, and $0.018\ M_{\odot}$ for 253-1536b (see Table 1). Both 216-0939 and 253-1536a are more massive than the upper limit of $0.034\ M_{\odot}$ found for the Orion Trapezium cluster proplyds in Paper I.

Both disks 216-0939 and 253-1536a are resolved. An elliptical Gaussian fit to the visibilities gives a size of $1''.5 \times 0''.3$

Table 1
Disk Fluxes and Masses

Proplyd Name (a)	F_{obs} (mJy) (b)	rms (mJy) (c)	M_{disk} ($10^{-2} M_{\odot}$) (d)	Disk Radius (AU) (e)	SpT (f)
216-0939	91.9	1.3	4.50 ± 0.06	291	K5
253-1536a	134.2	1.0	6.62 ± 0.13	282	Unknown
253-1536b	37.5	1.0	1.84 ± 0.04	<60	M2.5

Notes. (a) Proplyd designation based on the nomenclature of O’Dell & Wen (1994). (b) Integrated continuum flux density from the disk. (c) 1σ statistical error. (d) Disk mass (error does not include uncertainties in the flux scale of $\sim 10\%$). (e) Size of submillimeter emission determined using uvfit in MIRIAD. (f) Spectral type of embedded star from Hillenbrand (1997).

at a position angle of 174° (measured east of north) for disk 216-0939, which corresponds to a disk radius of ~ 300 AU and inclination $\sim 80^\circ$. The fit to disk 253-1536a gives a size of $1''.4 \times 0''.6$ at a position angle of 73° , corresponding to a radius of 280 AU and inclination of $\sim 65^\circ$. The secondary disk, 253-1536b, is unresolved, implying a radius < 60 AU.

4. DISCUSSION

4.1. Massive Disks and Planet Formation Capability

We found in Paper I that the disk mass distribution in the Trapezium cluster is truncated, with a lack of massive disks ($M > 0.034 M_{\odot}$) relative to Taurus and ρ Ophiuchus. As discussed in Paper I, the relatively low disk luminosities in the center of the Trapezium cluster cannot be due to heating from the O stars because that would operate in the opposite way to produce higher submillimeter fluxes for a given dust mass. The dust opacity in disks is unknown and a lower value in the Trapezium cluster disks, due to substantial grain growth, might explain the discrepancy (Pollack et al. 1994; Ossenkopf & Henning 1994). However, given that the cluster disks tend to have smaller sizes than the massive Taurus disks and the objects in this Letter, a more reasonable interpretation for the truncation of the Trapezium cluster disk mass distribution is the loss of the outer edges of the largest disks due to photoevaporation. Our finding here, of more massive disks beyond the Trapezium cluster, reinforces this interpretation. Proplyds 216-0939 and 253-1536 show no signs of photoevaporation and are similar in size and mass to the largest disks seen in Taurus.

Stellar encounters are much more common in the Trapezium cluster than in the more sparsely populated lower mass star-forming regions. Although Scally & Clarke (2001) found that they are an insignificant factor in disk destruction at the 1–2 Myr age of the cluster, Olczak et al. (2006) reasoned otherwise based on more detailed modeling of the disk–disk interaction and considering encounters with massive stars. Our disk mass measurements provide an important constraint on these theories. The most massive disk we have measured here, $0.066 M_{\odot}$, is almost twice that of the most massive disk we observed in the Trapezium cluster, $0.034 M_{\odot}$. If this discrepancy were only due to stellar encounters, it would require not only a close encounter but also a high stellar mass ratio: < 1000 AU for $M_2/M_1 = 90$ (Olczak et al. 2006). Yet, these same conditions imply a very high photoevaporative loss rate due to an O star. The low disk masses within the Trapezium cluster together with the high disk masses at larger distances firmly establish photoevaporation as the dominant disk erosive agent.

Counting 216-0939 and the two resolved disks in the binary 253-1536, we have measured the masses of three disks. Unless they have very flat surface density profiles, all satisfy the mass and size requirement to form a planetary system on the scale of our own; $M > 0.01 M_{\odot}$ within 60 AU (Paper I). Clarke (2007) stated that the $880 \mu\text{m}$ emission may become optically thick in such compact disks. But for the Beckwith et al. (1990) dust opacity we have used here, $\tau = \kappa \Sigma \approx 0.1$, where the average surface density, $\Sigma = 4 \text{ g cm}^{-2}$, for a face-on disk with $M = 0.01 M_{\odot}$ and $R = 60$ AU. The innermost regions may be optically thicker if the surface density strongly increases and τ may approach unity for edge-on disks such as 216-0939 but we did not see a correlation between flux and disk orientation in Paper I and believe that our observations are a good measure of the amount of small grains in the disks. There may well be undetected centimeter-sized and larger particles in the proplyds (e.g., Wilner et al. 2005). These massive silhouette disks at large distances from θ^1 Ori C have no detectable free–free emission at the mJy level and are good candidates for longer wavelength observations to study the larger grain population. It is important to keep in mind, of course, that the main uncertainty in any mass estimate based on the dust continuum is the gas-to-dust ratio.

4.2. The Binary Proplyd 253-1536

The *HST* image of proplyd 253-1536a by Smith et al. (2005) shows that it is very large, classified as a “giant,” with a radius $0''.75 = 300$ AU. A neighboring star lies only $1''.1$ (440 AU) away, with a low probability ($< 2\%$; Köhler et al. 2006; Reipurth et al. 2007) of chance alignment. Our SMA observations reveal substantial dusty disks around both stars with masses of $0.066 M_{\odot}$ and $0.018 M_{\odot}$. There is no evidence for any circumbinary material in the *HST* or SMA data, which is not surprising given the large separation.

Binary stars are important, not only because they make up a significant fraction of stars in the Orion Nebula (Petr et al. 1998; Köhler et al. 2006; Reipurth et al. 2007) but also because at least 20% of extra-solar planet discoveries are hosted by binary star systems (Raghavan et al. 2006; Desidera & Barbieri 2007; Eggenberger et al. 2007). However, millimeter wavelength detections of binary protostars in Taurus-Auriga (Jensen et al. 2003) and ρ Ophiuchus (Patience et al. 2008) generally find disks only around the primary stars. This agrees well with numerical models of core fragmentation which predict a higher disk mass around the more massive star (Bate 2000).

Rodríguez et al. (1998) found massive disks ≈ 0.01 – $0.05 M_{\odot}$ toward each of the binary protostars in L1551, the range due to the uncertain contribution from free–free emission at the long 7 mm wavelength of the observations. These are deeply embedded Class 0 protostars, however, with substantial circumstellar material and no clear dividing line between envelope and disks. Jensen et al. (2003) detected two disks in the HK Tau binary system but with low masses, $< 0.0019, 0.003 M_{\odot}$. The binary proplyd 253-1536 stands out as the first example of two optically visible stars each with sufficient mass to form a solar system.³ Their separation, > 440 AU in projection, is large enough that both the evolution of the disks and their prospects for planet formation can be considered independently of each other (Beckwith et al. 1990; Desidera & Barbieri 2007).

³ The triple system, UZ Tau EW studied by Dutrey et al. (1996) and Jensen et al. (1996) contains one star, UZ Tau E, with a disk mass high enough to potentially form a solar system. However, the stars of the accompanying binary UZ Tau W do not appear to have sufficiently high individual disk masses.

The discovery of this binary disk system was serendipitous. The disk around the optically brighter member of 253-1536 is too small to be seen in the glare of the star in the *HST* data. Optical images reveal the presence of similarly sized disks in the Trapezium cluster only through the presence of their photoevaporative tails. If the 253-1536 system was closer to the cluster center, both disks would be more apparent. There are probably many other more small disks in Orion that are not being photoevaporated and therefore not being detected by *HST* imaging.

The optically fainter star, 253-1536a has the larger and more massive disk. It is spatially resolved in both the *HST* and SMA data. Unfortunately, it is impossible to meaningfully constrain the surface density profile without knowledge of the mid- and far-infrared spectral energy distribution. Smith et al. (2005) noted that the disk silhouette appeared slightly de-centered from the stellar position. The effect would be at the limit of the SMA resolution but is not seen. The position angle of the disk in the *HST* image also appears slightly smaller than the SMA image. These differences are probably due to lower density material that absorbs optical light but emits little in the submillimeter. We speculate that an asymmetric flaring of the disk, such as seen in 216-0939, could produce this effect.

As a binary system, the two circumstellar disks in 253-1536 formed at the same time. Yet they have quite different masses and radii. The stellar masses play a large role in the initial disk conditions and subsequent evolution. Jensen et al. (2003) noted that the HK Tau binary has a stellar mass ratio close to unity and that other binaries with disk detections only around the primary had higher mass ratios. Although the optically brighter star 253-1535b is known to be of spectral type M2.5 (Hillenbrand 1997), the spectral type of 253-1535a with the larger disk, is unknown. It is fainter by a factor of 40 in $H\alpha$ (Reipurth et al. 2007), by a factor of 6 at $2.2\ \mu\text{m}$ (Köhler et al. 2006), and by a factor of 1.7 at $10.4\ \mu\text{m}$ (Nielbock et al. 2003). The nearly edge-on disk obscures a considerable fraction of the light at these wavelengths, however, and a spectrum is required for definitive typing and to determine the stellar mass ratio in this system. With this information, this system will be an important benchmark for comparison with theories of disk formation and early evolution.

5. CONCLUSIONS

We have detected strong $880\ \mu\text{m}$ emission from two silhouette disks in M43, just north of the Orion Trapezium cluster. The implied disk masses, $0.045\ M_{\odot}$ and $0.066\ M_{\odot}$, are the largest yet discovered in this massive star-forming region and strengthen our conclusion from Paper I that Orion disks likely had similar initial properties to those in the lower mass and less crowded Taurus-Auriga and ρ Ophiuchus regions.

We have also found that each star in the binary system 253-1536 possesses its own disk. Only the larger disk is visible in *HST* images but our SMA data, at comparable $0''.2$ resolution, reveal a $0.018\ M_{\odot}$ disk around the optically brighter star. Both disks in this binary have sufficient mass within 60 AU radius to form planetary systems on the scale of our own but their different masses and sizes demonstrate that the disks may have formed with quite different initial conditions or that their evolution is strongly dependent on additional parameters than time alone.

Our SMA survey of circumstellar disks in Orion both in and beyond the Trapezium cluster shows that about half the mass

can be lost in the outer edges of disks around stars within 0.2 pc of θ^1 Ori C but large, massive disks can survive beyond 1 pc. Further observations of a statistically representative sample of disks at intermediate distances are necessary to determine the sphere of influence of this O6 star more precisely. Additional observations are also required to better characterize the upper end of the Orion disk mass distribution. Finally, the high disk masses that we have observed would be detectable out to 2 kpc and suggest that studies of other H II regions could be fruitful.

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