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Protoplanetary disk masses in the Orion nebula cluster

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Abstract. We present the results of an 850 μm Submillimeter Array survey of protoplanetary disks in the Orion Nebula cluster, conducted to study the impact of ultraviolet radiation from massive stars on protoplanetary disk properties. A clear disk mass distance dependence exists in the Orion Nebula cluster with higher disk masses found at increasing distances from θ^1 Ori C, the most massive star in the region. Mass-loss due to external ultraviolet radiation becomes negligible for disks located beyond 0.3 pc from θ^1 Ori C. The disk mass and size distributions are consistent with the formation of Orion disks ~ 2 Myr ago with similar properties to disks found in low-mass star forming regions like Taurus, followed by subsequent photoevaporation down to smaller masses and sizes depending on their proximity to θ^1 Ori C. The fraction of surveyed Orion disks with the potential to form Solar system analogs is ~ 18%, suggesting the potential for forming planets is not lower than in star forming regions that lack massive stars.

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

1. Introduction

As the birthsites of planets, the fundamental properties of circumstellar disks around young stars provide very important constraints on the process of planet formation. While most protoplanetary disk studies to date have focused on young stars in the nearby Taurus-Auriga and ρ Ophiuchus dark clouds, stars do not commonly form in such isolation. The majority of stars form in dense, clustered star forming regions

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(Lada & Lada 2003), which often contain massive, O-type stars. The ultraviolet radiation from these massive stars photoevaporates protoplanetary disks around nearby young stars, reducing the amount of material available for planet formation (Johnstone et al. 1998; Churchwell et al. 1987). There is also evidence, from studies of short-lived radionuclides in meteorites (Krot et al. 2005), that indicate our own Solar system originated in a massive star forming environment. Therefore, in order to understand not only our origins, but presumably the origins of most extrasolar planetary systems, we need to study disk properties in massive star forming regions.

The Orion Nebula cluster is the nearest, young massive star forming region to the Sun and is therefore a natural starting point for studies of disk properties in rich clusters. It is home to a star cluster of OB-stars called the Trapezium, which have carved out a cavity in their molecular cloud through their ionizing radiation, forming a "blister" HII region that has opened up, fortuitously, in our direction. The resulting low visual extinction towards the Orion Nebula cluster has allowed these young stars to be studied at optical to infrared wavelengths. The ~2 Myr old Orion Nebula cluster (Da Rio et al. 2010) of $\sim 10^4$ stars (Hillenbrand 1997) lies at a distance of 400 pc (Sandstrom et al. 2007; Menten et al. 2007; Kraus et al. 2007, 2009). The cluster is located in front of its host molecular cloud and has a high galactic latitude, so it suffers little contamination from foreground or background stars.

The Hubble Space Telescope (HST) took very detailed images of the Orion Nebula and revealed a very hostile environment, in which many of the low mass stars near the Trapezium cluster are being photoevaporated by the intense UV radiation from its most massive star, O6-type star θ^1 Ori C (O'dell & Wen 1994; Bally et al. 1998; Ricci et al. 2008). The disks are surrounded by tear-drop shaped morphologies, with bright heads facing θ^1 Ori C and tails facing away; they also decrease in surface brightness with distance from θ^1 Ori C, leaving little doubt as to the source of their illumination (McCullough et al. 1995). Their unique morphologies led the disks to be dubbed the Orion "proplyds", an acronym for PROtoPLanetarY DiskS in massive star forming regions. Well before the disks were imaged with HST, they were studied at centimeter wavelengths with the VLA by (Churchwell et al. 1987), who found they have mass-loss rates $\sim 10^{-7}$ $M_\odot$ / yr. Such high mass-loss rates implied very short lifetimes which conflicted with the existence of the Orion disks. Furthermore, the disk material would be diminished far too quickly for planet formation to take place, particularly in the core accretion scenario (e.g. Hubickyj et al. 2005). But the question of how much material was left within the photoevaporaing Orion disks still remained.

One of the best methods for estimating disk masses is from observations of optically-thin dust continuum emission at long wavelengths. Although molecular gas is the dominant component of disks, the dust dominates the opacity and is significantly easier to detect. Infrared wavelength observations are often used to indicate the presence of protoplanetary disks, however, such observations can only trace hot dust located near the central star, to a maximum distance of a few AU. Longer, submillimeter to millimeter, wavelength observations are necessary to detect cooler dust located

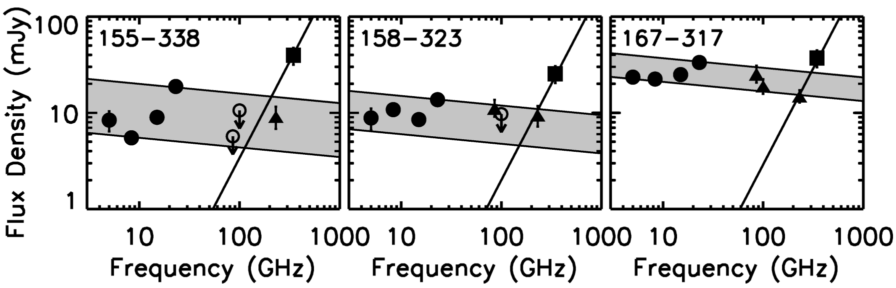

Figure 1. Spectral energy distributions for 3 proplyds detected in dust emission by the SMA at 850μm. Submillimeter fluxes are represented by squares, millimeter wavelength observations by triangles, and radio observations by circles. Fits to the ionized gas emission ($F_\nu \sim \nu^{-0.1}$) and disk emission ($F_\nu \sim \nu^2$) are overlaid to show their relative contributions. The grayscale shows the range of the ionized gas emission extrapolated to $850\,\mu$m (340 GHz) to show that the dust emission does not become significant until submillimeter wavelengths are reached.

further from the star, from a few AU to several hundreds of AU, tracing the majority of the disk volume where the mass lies. At these larger disk radii, the dust emission becomes optically thin, allowing a direct relationship between observed fluxes and disk masses from (Beckwith et al. 1990):

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

where d is the distance to the cluster, κ_ν is the dust grain opacity and $B_\nu(T)$ is the Planck function.

Pursuing the method described above, millimeter wavelength interferometers BIMA, OVRO, IRAM, CARMA and the SMA were used to study the Orion proplyds (Mundy et al. 1995; Bally et al. 1998; Lada 1998; Eisner & Carpenter 2006; Eisner et al. 2008). Interferometry is necessary at these long wavelengths, because proplyds near the Trapezium stars are clustered together just a few arcseconds apart and single dish telescopes do not have sufficient resolution to separate disk emission from individual stars. Most proplyds are being strongly photoevaporated and the ionized gas emission from the dense surrounding plasma swamps the weak thermal emission from the dust at centimeter to millimeter wavelengths (see Fig. 1). The dust emission dominates at higher frequencies, however, as it increases sharply ($F_\nu \sim \nu^{2-4}$) while the ionized gas slightly decreases ($F_\nu \sim \nu^{-0.1}$). Even at wavelengths as short as $1300\,\mu$m, the contrast between the disk and ionized gas emission is too small (see Fig. 1), making it extremely challenging to detect dust emission from the Orion proplyds at millimeter wavelengths. For this reason, millimeter interferometers were mainly sensitive to the ionized gas emission from the cocoons surrounding young Orion disks.

In 2005, a pilot study was performed with the world's first *sub*-millimeter interferometer, the Submillimeter Array (SMA) at $850\,\mu$m by Williams et al. (2005) towards a single field in the Orion Trapezium cluster. The field contained 23 Orion proplyds and these observations included 4 of the first clear detections of dust emission from the disks. These disks were found to have masses between ~ 0.01-$0.03\,M_\odot$, which showed for the first time that at least some of the Orion proplyds had sufficient mass to potentially form Solar system analogs. With the success of the pilot study observations, the project was expanded to measure the full disk mass distribution in Orion. The goal of this survey was to study the impact of ultraviolet radiation from nearby massive stars on disk properties and evolution and assess the potential for planet formation in the Orion Nebula cluster.

2. Submillimeter Array 850 μm observations and results

We initially surveyed 55 disks in 11 SMA fields at 850 μm in the Orion Nebula cluster, all located with 0.3 pc of θ^1 Ori C (Mann & Williams 2009). We detected 28 of the 55 disks at $\geq 3\,\sigma$. Before calculating disk masses, we needed to correct for contributions from the ionized gas and background molecular cloud emission for each disk. We constructed full radio-submillimeter spectral energy distributions (SEDs) for the 28 Orion proplyds, like those shown in Fig. 1, and subtracted off the maximum contribution of the ionized gas emission at 850 μm. Next, we corrected for the background molecular cloud emission in the region by simulating the response of the SMA to an 850 μm SCUBA map taken on the JCMT by (Johnstone & Bally 1999). For each observed SMA field, the corresponding SCUBA data were Fourier transformed and sampled over the same *uv*-tracks as the observations and images were produced in the same way as the observations. We measured the background flux at the position of the disk within each simulated field and subtracted this contribution from the observed SMA fluxes to get the corrected dust-disk fluxes.

We then used equation (1) to convert the dust-disk fluxes to disk masses, using a distance of $d = 400\,\mathrm{pc}$, a dust grain opacity of $\kappa_\nu = 0.1(\nu/1000\,\mathrm{GHz}) = 0.034\,\mathrm{cm}^2\,\mathrm{g}^{-1}$, and a dust temperature of $T = 20\,\mathrm{K}$, which is the average for disks in Taurus and ρ Ophiuchus (Andrews & Williams 2005, 2007a). Uncertainties hidden within the opacity prescription, in particular, with respect to the gas-to-dust ratios and the dust grain size distributions, affect the determination of disk masses. Given these uncertainties, it is instructive to use the same temperature and opacity as the Taurus and ρ Ophiuchus studies to simplify the comparison of disk properties. The calculated Orion disk masses are plotted in the top panel of Fig. 2. We also plot the SMA survey completeness, which was not straightforward because it depended on many factors, including the location of the disk in each field, and the contributions of free-free and background emission. We derived the mass sensitivity by determining the fraction of sources that could be detected at $\geq 3\sigma$ at each disk mass, depending on the above-mentioned characteristics. We found that the SMA survey is 100% complete for disk masses $\geq 0.0084\,M_\odot$, and 85% for a factor of 2 lower in mass, before dropping off steeply towards lower disk masses.

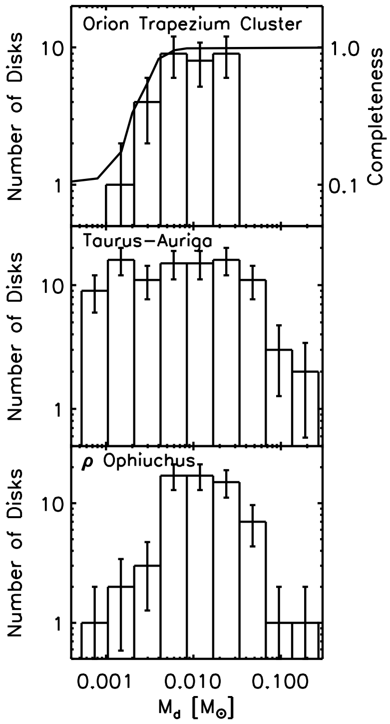

Figure 2. Differential disk mass distribution in the Orion Nebula cluster within 0.3 pc of θ^1 Ori C (above), compared with distributions in Taurus and ρ Ophiuchus (below). The error bars for the distributions are $\sqrt{N}$. The disk mass sensitivity of the Submillimeter Array survey is indicated by the continuous line in the top panel. Binning begins at 0.0084 $M_{\odot}$ to separate complete and incomplete samples. The number of disks per logarithmic mass bin is approximately constant for masses 0.004 − 0.04 $M_{\odot}$ in all three regions but there are no disks with masses $\gtrsim$ 0.04 $M_{\odot}$ in the Orion Nebula cluster within 0.3 pc of θ^1 Ori C.

Also plotted in Fig.2 are the disk mass distributions for similarly-aged disks taken from the JCMT-SCUBA surveys of disks in Taurus and ρ Ophiuchus by (Andrews & Williams 2005, 2007a). For the central mass bins, spanning disk masses between 0.004-0.04 $M_{\odot}$, the number of disks per logarithmic mass is approximately constant and similar across all 3 star forming regions. The differences become apparent at the high mass end of the distributions. Orion is lacking disks more massive than $\sim 0.04\,M_{\odot}$, which is not an observational bias as the survey is most sensitive to the high mass (brightest) disks in the region. If the Orion disk distribution was similar to Taurus (or ρ Ophiuchus), we would expect to find at least 8 (5) disks with masses $\gtrsim 0.04\,M_{\odot}$ in our sample. With this expectation, the probability of detecting none is 0.03% (0.7%). Two-tailed Kolmogorov-Smirnov (KS) tests on the disk distributions above 0.0084 $M_{\odot}$, for which all observations are fully complete, show that the Orion disk distribution is statistically different from the distributions in both Taurus and ρ Ophiuchus with $> 5\sigma$ significance. We compared disk luminosities to see if the

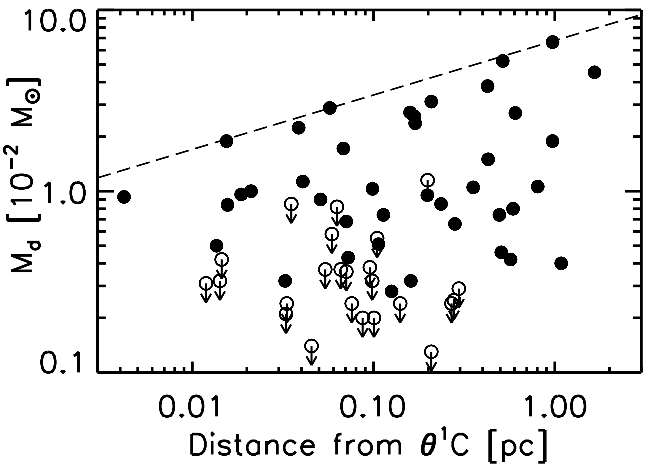

Figure 3. Circumstellar disk masses in the Orion Nebula cluster plotted against their projected distance from the O-type star, θ^1 Ori C. Filled circles represent detections, while open circles are the $3\,\sigma$ upper limits for the non-detections. The maximum disk mass envelope is traced by the long dashed line across the top, to expose the absence of massive disks near θ^1 Ori C and the trend of increasing disk mass with distance.

difference could be attributed to the flux-mass conversion but found the disk distributions remained significantly different.

The inner 0.3 pc of the Orion Nebula cluster is lacking the most massive ($\gtrsim 0.04\,M_\odot$) disks found in isolated, low-mass star forming regions like Taurus. Theoretical models of disk photoevaporation (Johnstone et al. 1998; Störzer & Hollenbach 1999; Adams et al. 2004; Clarke 2007) predict that mass-loss is expected to be high in the outer parts of the largest disks. But mass-loss should decrease as the erosion progresses towards smaller disk radii, with the gravitationally bound inner disk potentially surviving for several Myrs. In fact, many of the disks surveyed within 0.3 pc of θ^1 Ori C are unresolved by HST observations, with inferred sizes $< 0.15'' \sim 60$ AU. The smaller disk sizes and masses observed in Orion is consistent with the idea that the outer edges of the Orion disks have been photoevaporated away by ultraviolet radiation from nearby massive O-stars. When we more directly compare disk properties in Orion and Taurus, we find the maximum disk mass in Orion is a factor of ~ 3 times lower than in Taurus, which should correspond to a factor of ~ 3 in reduction in size, if we assume a surface density profile, $\Sigma \sim r^{-1}$, which has been uniformly observed for many disks in low mass star forming regions (Andrews & Williams 2007b; Andrews et al. 2009). If Orion disks started out with initial properties like those in Taurus, which have a median size of 200 AU, and a range of 100-700 AU, we would expect them to be photoevaporated to sizes $\lesssim 70$ AU and masses consistent with the SMA survey. We, therefore, find the masses and sizes of the Orion proplyds are consistent with having an initial distribution of disk properties like those found in Taurus.

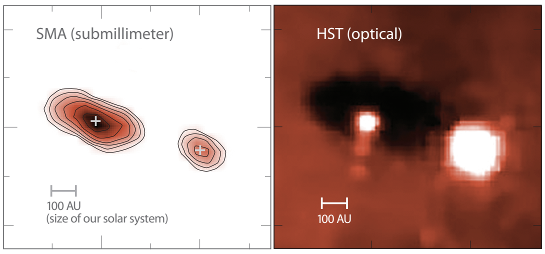

Figure 4. A Submillimeter Array image of the 850 μm continuum emission from the binary system 253-1536 in the Orion Nebula (left). The HST Hα discovery image was taken directly from Smith et al. (2005) and is shown using the same $2.5'' \times 2.5''$ field of view (right). SMA contours begin at the 5σ level, where σ=1 mJy beam^{-1} is the rms noise level in the map, and each step represents a factor of 1.5 in intensity.

Next, we explored the extent of the disk mass truncation in Orion by surveying disks at a range of distances from θ^1 Ori C (see Fig.3; Mann & Williams (2010) and we found a clear dependence of maximum disk mass on increasing distance from θ^1 Ori C. In fact, disks more massive than 0.04 $M_\odot$ are present in Orion at distances beyond 0.3 pc of θ^1 Ori C, revealing the formation of massive disks is not precluded in rich clusters with massive stars. Furthermore, the range of masses observed for disks located beyond 0.3 pc of θ^1 Ori C is similar to that observed in Taurus, providing direct evidence that Orion disks likely formed with properties like disks in Taurus, with subsequent photoevaporation depending on their proximity to θ^1 Ori C. Mass-loss driven by UV radiation from θ^1 Ori C is negligible beyond a distance of 0.3 pc, with a maximum statistical difference between the potentially Solar system forming disks within and beyond this distance (see also Johnstone et al. 1998; Störzer & Hollenbach 1999).

Despite the clear signs of disk erosion observed in Orion, we find ~ 18% of our surveyed disks could potentially form Solar system analogs, as they contain 0.01 $M_\odot$ within ~ 60 AU, compared with ~ 13% of Taurus disks. Therefore, the potential to form planets is not diminished in Orion when compared with isolated star forming regions that lack massive stars.

3. Binary system 253-1536

One of the most compelling objects in the entire SMA survey was the binary system 253-1536 in the Orion Nebula cluster, discovered through HST-imaging by Smith et al. (2005); see Fig.4. Located ~ 1 pc away from θ^1 Ori C, this system has a very low (< 2%) probability of chance alignment (Köhler et al. 2006; Reipurth et al. 2007). Only one disk is obvious in the HST image, a prominent disk around the primary star (Ricci et al. 2011), which is consistent with all existing observations of widely separated binaries that revealed low mass to non-existent disks around the secondary components (e.g. Jensen & Akeson (2003); Patience et al. (2008)).

SMA observations at 850 μm towards the binary system 253-1536 revealed protoplanetary disks surrounding each of the stars. Even more surprising was that the masses of each of these disks were high enough (0.07 $M_\odot$, 0.02 $M_\odot$) to potentially allow the formation of Solar system analogs (Mann & Williams 2009). This system stands out as the first clear example of a binary system in which each star is surrounded by a massive protoplanetary disk. Observations like these are adding to an increasing body of evidence showing that binaries do not necessarily disrupt protoplanetary disk formation and evolution, as long as the separation between stars is large enough, $\gtrsim$ 100AU (Mathieu et al. 2000; Duchêne 2010). Multiple star systems make up a substantial fraction of stars in our Galaxy (Mathieu 1994) so if disks can form and persist around individual stars of binary systems, it raises the overall prospects for planet formation.

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