ALMA Observations of Molecular Gas Emission from a Protoplanetary Disk in the Orion Nebula Cluster

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Background

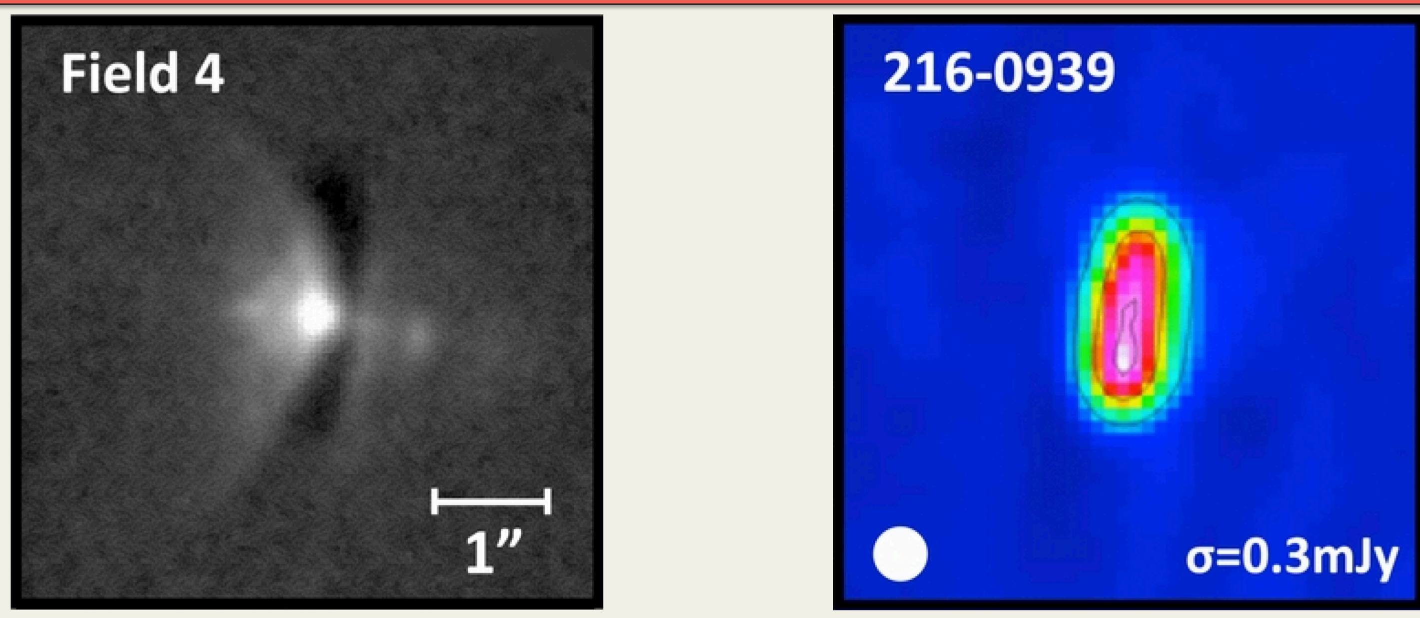

Figure 1: (left) HST (Hα) observation from Smith et al. (2004). (right) ALMA 856 μm continuum observation from Mann et al. (2014) with a FWHM resolution of 0.5". Image sizes are 5"×5".

Spatially resolved submillimeter observations of dust and gas in protoplanetary disks provide insight into the location and amount of material available for planet formation. By necessity, most such studies have focused on resolving disks in nearby, low-mass star forming regions, due to the limited sensitivity and angular resolution of submillimeter interferometers. However most stars, likely including our Sun, form in denser environments near O-type stars, such as the Orion Nebula. Previous submillimeter studies of disks in Orion have yielded marginally resolved observations of continuum emission only. For the first time, using ALMA, we have significantly detected and resolved gas emission from disks in Orion.

Observations

We present ALMA observations of d216-0939, a pre-main-sequence K5 star surrounded by the largest, most distant disk imaged in Orion. Observations are at wavelengths around 856 μm, corresponding to the HCO^+(4-3), CO(3-2), HCN(4-3), and CS(7-6) rotational transitions, with spatial resolution of 0.5", and velocity resolution of 0.4 km/s. The observations represent 22 min on source as part of a Cycle 0 survey by Mann et al. (2014). Baselines shorter than 70 kλ were excluded to minimize large-angular-scale cloud contamination. Channel maps for HCO^+(4-3) are shown in Figure 3. Other lines are not shown as CO(3-2) is dominated by background cloud emission, CS(7-6) was not resolved, and HCN(4-3) data is currently being analyzed.

Smith et al. (2004) noted significant asymmetry, with the northern portion being ~50% larger than the southern portion. In contrast, the 856μm continuum map shows the southern portion of the disk to be brighter. We also note unresolved high relative velocity emission coming from near the star shown in Figure 2. This could be a signature of young giant planet. The disk emission matches the profile for a ~2 $M_\odot$ central star, consistent with the color and expected age of the system.

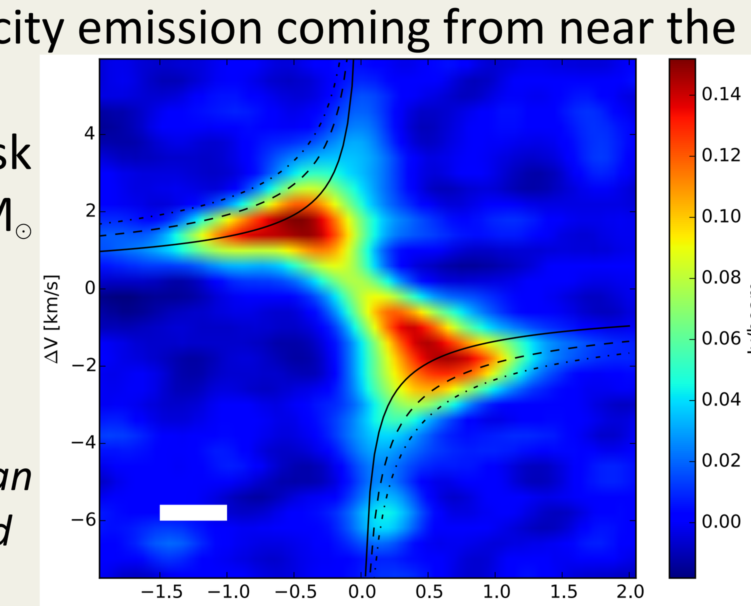

Figure 2: position-velocity diagram for HCO^+(4-3) emission. Black curves are Keplerian velocity profiles for stellar masses of 1, 2, and 3 $M_\odot$. White box shows the resolution.

Modeling

We fit the data using a ray tracing code assuming local thermodynamic equilibrium (LTE). Position offset and systemic velocity were fitted using a simple grid search and a typical model disk. We then fit the model using `emcee`, an affine invariant Markov Chain Monte Carlo (MCMC) algorithm (Foreman-Mackey et al. 2013). This fitting method works particularly well with multidimensional degenerate parameter space and also allows us to characterize the uncertainty on our best fit parameters.

We fit the HCO^+(4-3) and CO(3-2) emission (excluding contaminated channels) individually and together, and are currently working to incorporate the HCN(4-3) emission. We chose to exclude the 8 most blue-shifted channels in our fitting to avoid the excess high-velocity emission close to the star (see Figures 2 & 3). We did not fit the SED, as spectral data was either not available or contaminated by background emission.

Table 1: Best fit parameters from fitting CO(3-2) and HCO^+(4-3) emission together. Uncertainties are relative and based solely on the fits; they do not reflect systemic uncertainties such as flux or distance. Bracketed values were fixed. The distance was fixed at 400 pc, v_{turb} to 0.01c_s, γ to -1, and v_{sys} to 10.67 km/s. q and γ are the power law indices for temperature and density respectively. Z_q and R_c are the truncation distance for the vertical temperature and radial surface density respectively.

Parameter	CO & HCO^+ (best)	CO & HCO^+ (median)
q	-0.24	-0.25 ± 0.02
$M_{\rm disk}$ ($M_\odot$)	[0.045]	[0.045]
R_c (AU)	850	1000^{+300}_{-200}
M_* ($M_\odot$)	2.20	2.19 ± 0.04
$z_{q,150}$ (AU)	73	67^{+10}_{-8}
$T_{\rm mid,150}$ (K)	24.7	25.1 ± 0.8
$T_{\rm atm,150}$ (K)	86	78^{+14}_{-9}
$\log X_{\rm gas}$	$[-4], -10.04$	$[-4], -10.00 \pm 0.06$
i (deg)	67.7	$67.2^{+0.6}_{-0.8}$
PA (deg)	-6.1	$-5.5^{+0.6}_{-0.7}$

Results: Planet Forming Potential and Possible Forming Gas Giant

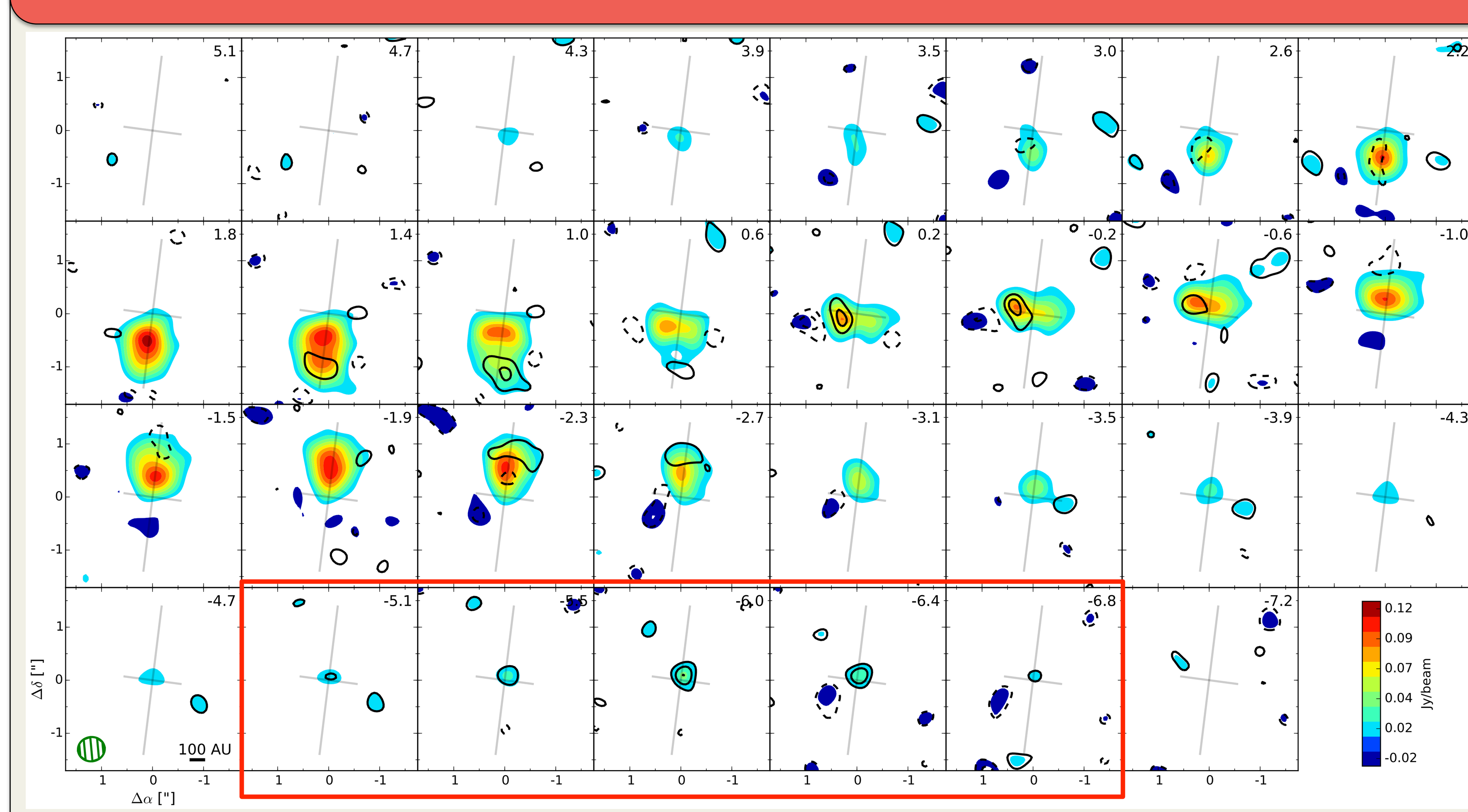

Figure 3: (left) Naturally weighted channel maps of HCO^+(4-3) emission. ΔV from line center is given in the upper right corner. Color map and contours start at 0.019 Jy/beam (3σ) with increments of 0.012 Jy/beam (2σ). Synthesized beam is marked in the bottom left corner. Contours are residuals from the best fit model given in Table 1. Red box indicates the excess high velocity emission.

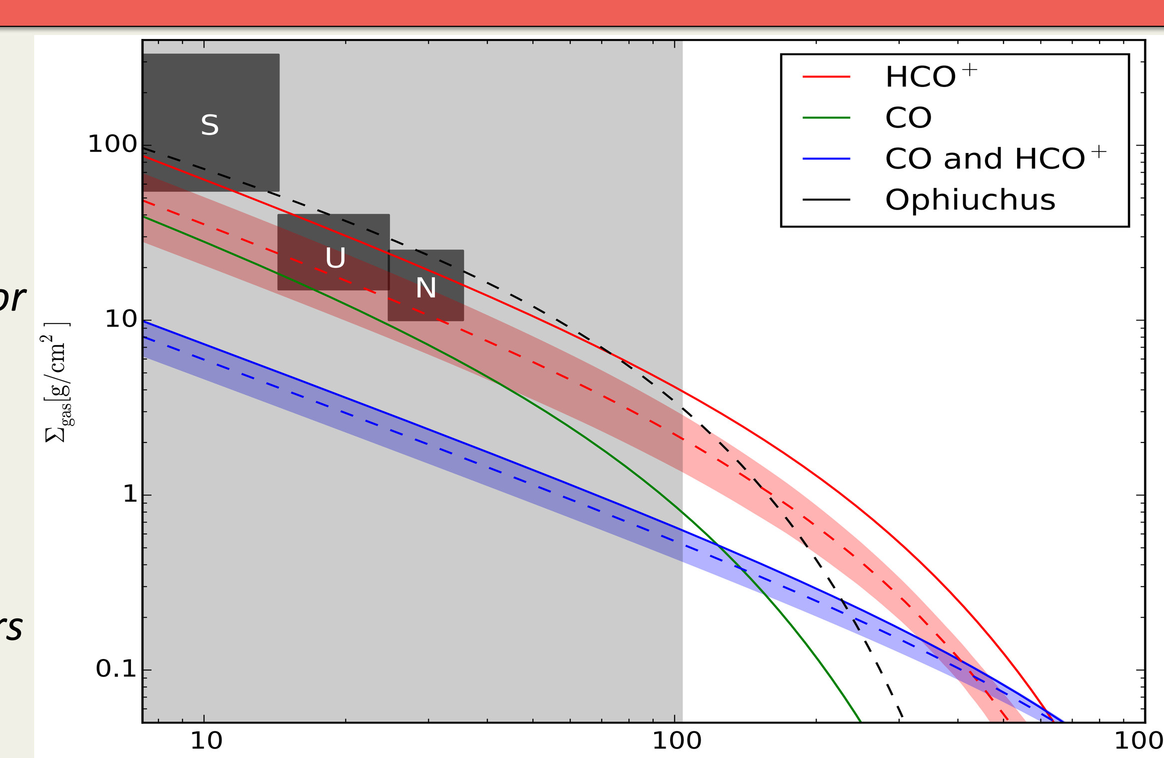

Figure 4: Radial surface densities derived for d216-0939 alongside the median profile for disks in Ophiuchus given by Andrews et al. (2009, 2010) (M_{disk}=0.06 $M_\odot$, γ=0.8, R_c=85 AU). Dark gray rectangular regions mark the surface densities for Saturn, Uranus, and Neptune in the Minimum Mass Solar Nebula (MMSN; Weidenschilling 1977). Light gray region marks the resolution limit of the ALMA observations.

Our best fit disk mass, when fitting HCO^+(4-3), is consistent with continuum measurements made by Mann & Williams (2009) and is similar to masses derived for disks in Ophiuchus. North-South asymmetry is noted, consistent with observations of the dust continuum. The surface density profile is similar to disks in the Ophiuchus low-mass star forming region and the MMSN, indicating significant planet forming potential. The velocity and position offset of the excess high velocity emission are consistent with a Keplerian orbit of 45±8 AU. From the integrated line flux, we estimate a gas mass of 7±3 $M_{Jupiter}$ in the feature. This feature could be the signature of a currently forming as giant planet.

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