Interpreting Spatial Distributions of ALMA DEC/O Sample Selections

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Abstract:

I investigated the clustering properties within a large-scale survey of protoplanetary disks that are being observed with the Atacama Large Millimeter/Submillimeter Array as part of the ALMA DEC/O Large Program. These disks were selected on a variety of features, but these may have unforeseen effects on any analysis carried out. For example, if the disks are not heterogeneous as expected, then any properties derived from their chemical analyses may be biased. Using Python, Jupyter Notebooks, and 3D plotting tools, I have investigated the clustering of the spatial distribution (density) of disks on the sky and the clustering of stellar masses. I investigated these properties for three out of the four regions targeted with DEC/O. While stellar mass was mostly uniform for Taurus and Lupus, Rho Ophiuchus had some clear separation in the lower (M-dwarf) and higher (GK-dwarf) populations. On the other hand, Taurus and Lupus had more sheet and filament-like structures than Rho Ophiuchus. These efforts will be followed up with more quantitative metrics that span more population properties. Such studies will be invaluable for putting the DEC/O sample into context in the broader population of planet-forming disks.

Introduction

My research this semester focused on interpreting the spatial distributions of the sample selection from the ALMA DEC/O Project. ALMA DEC/O is a Cycle 9 Large Program with ALMA led by Ilse Cleeves, my advisor for this project. DEC/O stands for the Disk-Exoplanet C/Onnection and has two major parts to it: the survey and the analysis. The survey aims to create a large-scale survey of protoplanetary disks that are more indicative of the stars which host exoplanets. This approach is in contrast to the large body of research surrounding more massive disks that are well-studied but are not representative of the majority of exoplanet forming disks. The analysis portion of DEC/O plans to use this data to understand the chemical evolution of planets that form out of disks. In selecting the samples for DEC/O, a few criteria were used to narrow down the number of targets to a reasonable amount of ALMA observing time but still remain statistically significant to allow the team to draw meaningful conclusions. The star forming regions (SFRs) selected for the sample Lupus, Rho Ophiuchus, Tau, and ChaI. In each SFR, twenty disks were selected. The disks and their SFRs were selected for four main reasons:

- **Distance:** all four SFRs are within 200 pc away.
- **Age**: all are relatively young, less than 4 Myr.
- **Host star**: M and GK dwarf hosts.
- **Minimum disk mass:** at least a Neptune-mass of gas in the disk based on the dust mass multiplied by an interstellar gas-to-dust ratio of 100.

What my thesis research aims to address is how these selection criteria affected the spread of the sample, since the criteria needed to be put in place in order to narrow down the scale of the project. These criteria, however, may have unforeseen effects on the overall conclusions drawn from the analysis. Additionally, it is helpful for researchers to have a visual aid in the spatial distribution of their data samples to put the overall sample into context with the larger SFRs.

Methodology

Due to time constraints, data was gathered from 3 of the 4 star forming regions in the DEC/O survey, leaving out the 20 sample disks from Chameleon I. To start, we used the “pandas” data analysis package in Python to upload the names of the sample sources from DEC/O into lists of strings from a .csv file to a Jupyter Notebook for each set of 20 disks in Lupus, Rho Ophiuchus, and Taurus. We ran these names through the “get_icrs_coordinates” function from the “coordinates” package of astropy, which uses the names of the input source to output its right ascension and declination from the International Celestial Reference System (ICRS) coordinates, and compiled those coordinates into separate lists for each SFR.

After retrieving the coordinates of the sample sources, we used similar methods to upload the distances from a .csv file which were collected using data from the Gaia spacecraft. Gaia, launched in 2013 and operated by the European Space Agency, conducts large-scale surveys of stellar parallaxes, providing us with essential distance measurements for nearby sources. Despite some inherent error in Gaia's parallax measurements, this methodology remained robust due largely to the deliberate selection of relatively nearby sources within 200 parsecs.

Once the spherical coordinates of right ascension, declination, and Gaia distances were obtained, we implemented the “spherical_to_cartesian” function, again in the “coordinates” package of astropy. This function converted these spherical coordinates to Cartesian coordinates, giving us the Xs, Ys, and Zs we needed to facilitate plotting. Utilizing the “matplotlib” Python package, we plotted each SFR individually and employed a color scale to qualitatively compare our selected variables' distributions within each region.

To establish a reference point and to gain insight into the appearance of these sources from different perspectives, we first employed our color scale to represent distances from the solar system, as defined by our previously obtained Gaia distance data. Red represented the furthest sources, while blue denoted the closest ones among each of the 20 disks analyzed in each of the 3 SFRs.

Subsequently, we plotted the stellar masses on the same color scale to discern the distribution of spectral types of the host stars within the disks. The color scale ranged from blue to red, signifying the least massive M dwarfs (as small as 0.2 solar masses) to the most massive G stars (up to 1.1 solar masses), respectively. A few of the host stars included in the DEC/O sample reported masses as high as 1.3 solar masses, indicating possible binary systems where reported masses encompass the combined masses of multiple stars, as opposed to true F type stars, as is the case for HP Tau (Rizzuto et al., 2020).

<u>Results</u>

Using the data and code derived from our methodology section, we compiled and qualitatively analyzed plots for each of the 3 SFRs in question. The initial set of plots, depicted in Figure 1, utilizes a color scale to illustrate the distribution of distances to each source with respect to the Solar barycenter. The range of distances, in parsecs, is sometimes clustered like Lupus, and sometimes spans a substantial range like Taurus or Rho Ophiuchus.

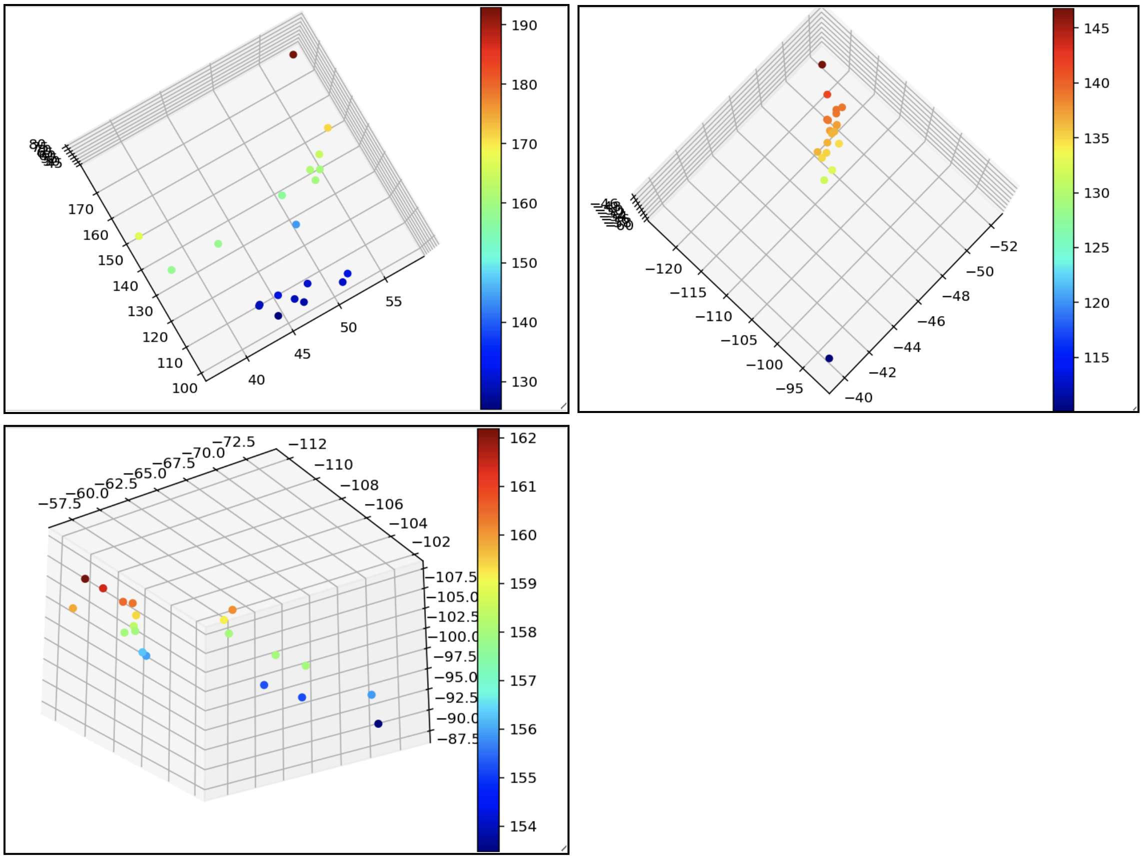

Figure 1: *Clockwise from top left: Taurus (1A), Rho Ophiuchus (1B), and Lupus (1C) plotted spatially. Color scale shows distances of sources from nearest (blue) to furthest (red). Orientation of plots meant to optimize perception of distance from Earth. All units are in parsecs.*

In Figure 1A, representing the Taurus region, we observe a relatively smooth gradient of distances to sources. The disk appearing on the graph as a deep red, which is over 190 parsecs away from us, is the one exception to this, as it is nearly 20 parsecs further from Earth than the next furthest disk. In contrast, the other disks in the Taurus region appear to have consecutive spacing of no more than 10 parsecs. Similarly, Figure 1B, representing Rho Ophiuchus, presents a rather compact cluster of disks stretched in one dimension from closest to furthest, with one outlying disk at about 20 parsecs closer to Earth. In Figure 1C, we find that Lupus has a considerable laterally spread configuration, with disks following a smooth gradient in distances and no notable outliers.

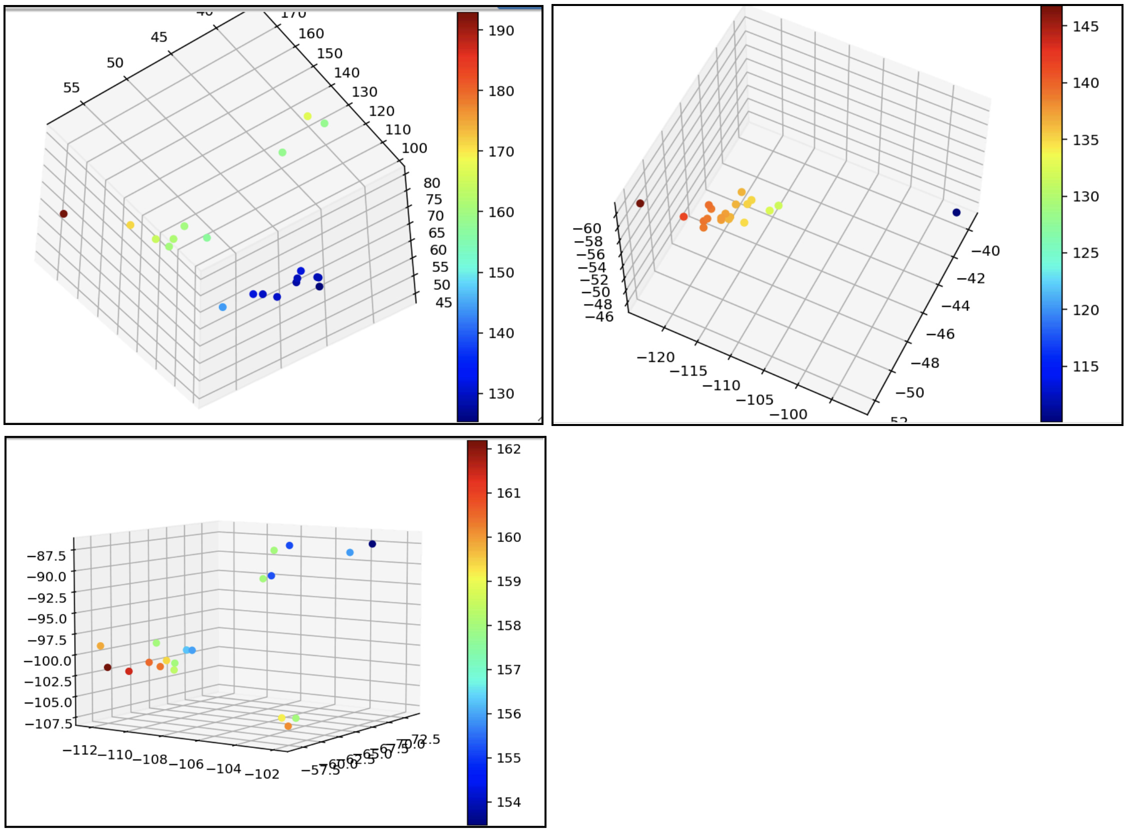

Figure 2: *Clockwise from top left: Taurus (2A), Rho Ophiuchus (2B), and Lupus (2C) plotted spatially. Color scale shows distances of sources from nearest (blue) to furthest (red). Orientation of plots meant to optimize perception of structures found within each region. All units are in parsecs.*

Figure 2 shows the same plotted data as those shown in Figure 1, however, these plots are rotated to optimize our observations of structural features within the SFRs. Figure 2A showcases, most notably, a filament structure within Taurus made up by its disks closest to Earth, appearing on the plot as a blue line of disks. Taurus may additionally feature a planar structure of disks composed by those at the intermediate distances from Earth, appearing as a green sheet of disks in the plot. Figure 2B renders similar conclusions for Rho Ophiuchus as Figure 1B, reinforcing the initial interpretation of a dense formation of disks stretching from nearest to furthest from Earth, with one outlier appearing in the foreground closest to us. Figure 2C highlights the importance of rotating the 3D plots for a new perspective, as it tells a much more interesting story of the structure of Lupus than Figure 1C. From this we gather that there are 3 distinct subregions within Lupus made up by the selected sample of disks: A small cluster of 3 disks emerge towards the bottom of the plot positioned at a median distance; A nearby handful of disks at the top right of the plot takes shape as a loose cluster; And a third group of disks with a similar spatial size appear to the left of the plot, but feature a much denser cluster.

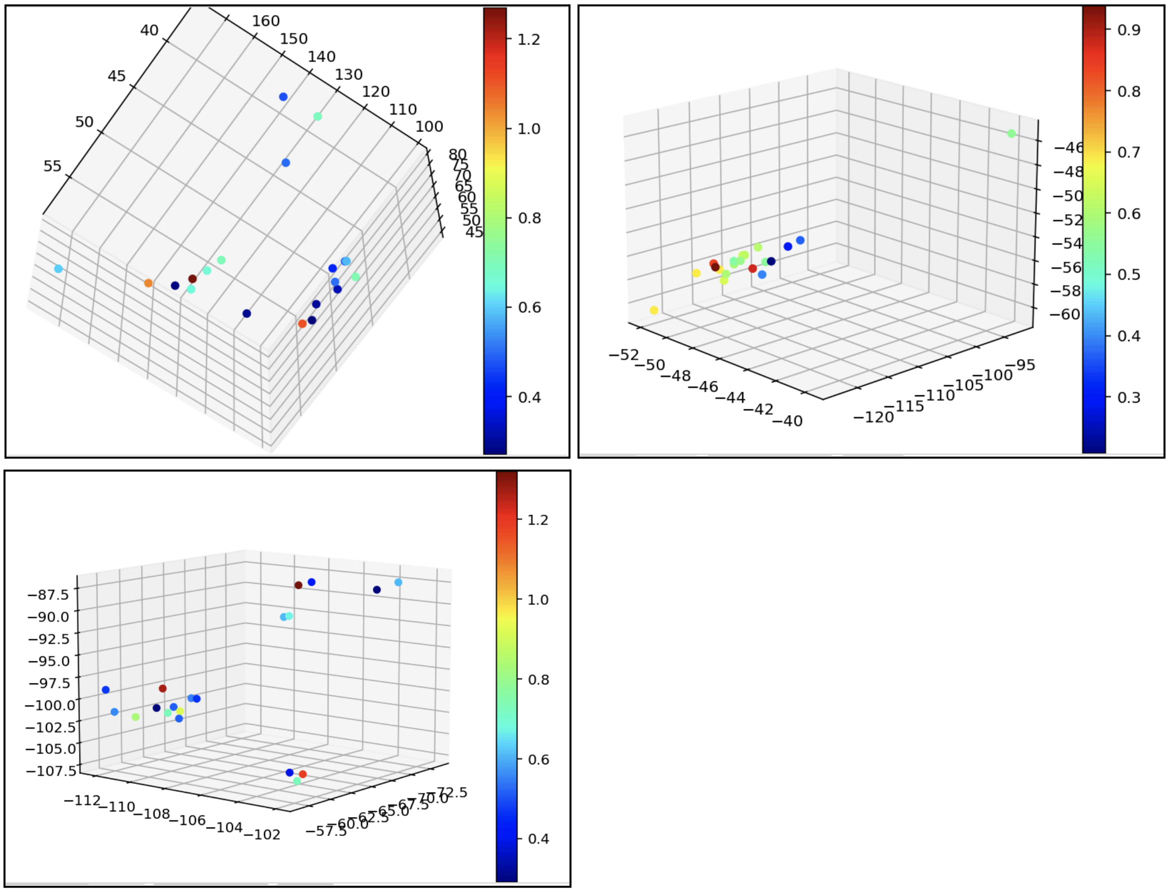

Figure 3: *Clockwise from top left: Taurus (3A), Rho Ophiuchus (3B), and Lupus (3C) plotted spatially. Color scale shows the distribution of stellar masses in units of solar masses ranging from least massive (blue) to most massive (red). Orientation of plots meant to optimize perception of structures found within each region and to ensure visibility of all points. Units for all axes of the 3D plot are given in parsecs.*

Figure 3 takes a stab at a new variable plotted along the color scale, this time allowing us to analyze the distribution of stellar masses within the SFRs. The most massive hosts in the sample, either G stars or the combined masses of binaries, show up towards the red end of the scale, while the least massive, the M dwarves, show up as blue. Figure 3A illustrates Taurus's varied spread of stellar masses, pointing to the potential to study the interactions between the disks with host stars of different masses. Conversely, Figure 3B for Rho Ophiuchus demonstrates spatial stratification of the stellar masses, with disks closest to us distinctly emerging as those with the smallest host stars, in contrast to those further from Earth emerging as those with the most massive host stars. Finally, Figure 3C reveals a relatively even spread of stellar masses, with notable diversity in host star sizes even across the localized substructures. From just a brief look at the plot, we observe host stars with masses indicative of both M and K stars present in each of the individual clusters featured in Figure 2C, as well as redder points indicative of G stars or binaries.

Discussion

Our analysis provides insights into the spatial distributions of sources and stellar masses within the star-forming regions, highlighting features for further study and thus contributing to our understanding of these dynamic astronomical systems. Despite there being the same number of disks in each region, we can see that there are variations in the spatial density of disks (not heterogeneous) as well as stellar masses in the different SFRs. In Taurus and Lupus, we see distinct subregions within the SFRs that may indicate some features of the birth environment, like filaments, sheets, or formation pathways – i.e., competitive accretion. On the other hand we have Rho Ophiuchus, which displays a clear segregation of stellar masses with the least massive stars towards one end of the field, with the most massive on the other end of the distribution.

Are these features truly reflecting physical processes or features of the birth environment? The distances are taken from the Gaia DR3 survey, which reports error up to 20% in sources nearest the galactic center. All of our targets are considerably closer, and have typical uncertainties on their distances of 4% (approximately 6 pc for many sources). Given that some of the features we see are of order this size in their width, there is a question of whether these structures truly exist.

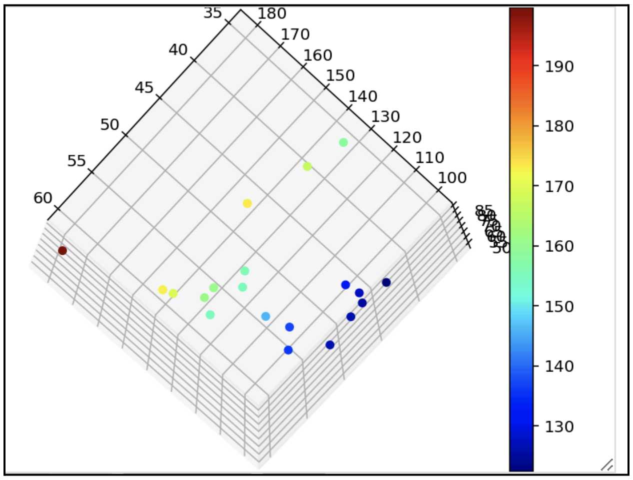

Figure 4: *3D disk distribution after uncertain distance values applied for the Taurus sub-sample. All units are in parsecs.*

To investigate this, we took the uncertainty from the HQ Tau disk in the sample as representative of error we might see across the DEC/O sample in a fractional sense, because the error propagated by Gaia is distance dependent. We normalized a set of random error values around this 4% value and added them randomly each of the Taurus disk's distances. We recreated the previous plots with these new perturbed distances to see if the features robustly appear. In Figure 4, we see that although the structures are indeed perturbed, the general features still stand, with the filament and the sheet both still largely remaining in their original observed forms.

Conclusions:

I have carried out a spatial analysis of the disks in the DEC/O sample. Lupus and Taurus have 3D structures present, while Rho Ophiuchus has a relatively dense structure, but with a single close by source spatially separate from the remaining 19 disks. Rho Ophiuchus is otherwise relatively clustered. In terms of their distribution of stellar masses, Lupus and Taurus have stellar host masses that are heterogeneous. Rho Ophiuchus seems to have clustered low and high mass subregions.

In terms of future steps, a primary goal will be to create the same plots for Chameleon I and to examine the impact of the distance error on the regions including the source specific uncertainties. The latter will be important especially when considering more inclined (edge-on) disks, where the astrometry is poorer given that the star is more obscured by the disk. The analysis carried out here has also been more qualitative in its observations. Thus a future goal is to conduct a more quantitative analysis using statistical tests to look at 3D clustering.

We have also focused on 3D density and stellar mass, but there are many other known variables from the sample that would be helpful to have visuals for, including the disk mass and radial size. In addition, the star forming regions tested here are all known to exist on the edge of the “Local Bubble” (see Figure 5), and thus knowing where these stars lie with respect to features in the Bubble will be helpful to further put the sample into context.

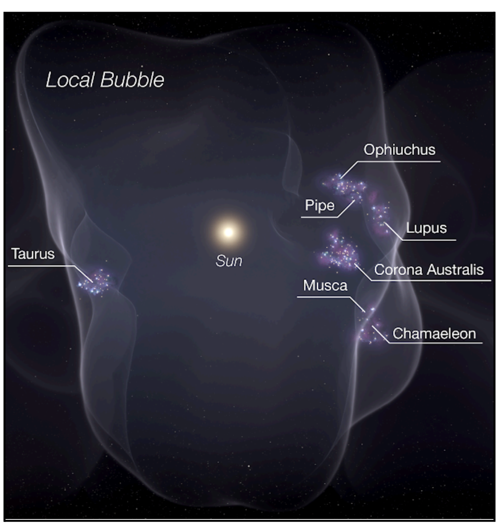

Figure 5: *Artists conception of the mapped edges of the Local Bubble with respect to the Sun and nearby SFRs. Image Credit: Catherine Zucker.*