Cataloguing Molecular Cloud Populations in Galaxy M100

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I. PROJECT OBJECTIVES

The goal of this project is to catalogue the molecular clouds in the spiral galaxy Messier 100 (M100) of the Virgo cluster, and study how different populations of clouds within the galaxy follow the relationships found in previously studied galaxies.

Molecular clouds are cold, dense regions of interstellar medium where gravity is able to overcome gas pressure, enabling them to be the sole location of star formation. An improved understanding of the structure of molecular clouds will provide insight into star formation. At masses greater than $10^5 M_\odot$, molecular clouds fall into the range of Giant Molecular Clouds (GMCs). However, due to M100's distance from earth (14.3Mpc), and the large resolution element of our observations compared to the size of typical GMCs, we are looking at complexes of GMCs called Giant Molecular Associations (GMAs). We will study whether traditional scalings extend to these larger, more massive regions.

II. EXPERIMENTAL DETAILS

This study is done using new-millimetre-wave data from the Atacama Large Millimeter/submillimeter Array (ALMA) interferometer in Chile. Although similar research has been done on other galaxies, ALMA provides a particularly well resolved data set, allowing us to resolve the centre and width of spectral lines, and thus measure the clouds' radial velocities and internal motions.

Although molecular gas is comprised mainly of molecular hydrogen (H_2), at GMCs' typically low temperatures of 10K, H_2 does not emit radiation. Instead, we obtained our spectral data from the next most abundant gas: carbon monoxide molecules's J=1-0 emission. From the measured carbon monoxide (CO) abundance, the mass of H_2 can be derived from the empirical X-factor relationship.

III. PRELIMINARY RESULTS

To begin our analysis, we recreated the Larson's Laws plots to test his scaling relationships for our M100 data.

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In Fig. 1, the luminous masses (M_{lum}) derived from the luminosity of CO, are plotted against the virial masses (M_{vir}) inferred from the velocity dispersion. The scaling line is the expected one to one ratio. Fig. 1 shows that the luminous masses are generally higher than the virial masses and that the nuclear clouds (blue) are more massive than the disk clouds (green).

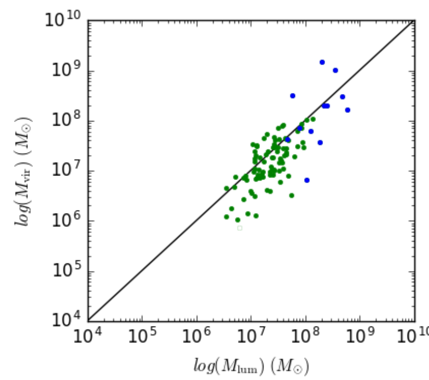

FIG. 1: Virial mass compared to the luminous mass of the GMAs. The black line is the expected one to one ratio, blue points represent nuclear clouds, and green represent disk clouds.

Fig. 2 shows luminous mass as a function of radius for each GMA, with the expected fit line as found in Solomon *et al.*(1987) for the Milky Way galaxy:

$$M_{lum} = 540 R^2 (M_\odot). \quad (1)$$

The nuclear GMAs are more massive for their sizes, compared to most disk clouds of equivalent sizes.

In Fig. 3, the radii of GMAs were also plotted against velocity dispersion, which represents the mean local speed of the cloud. Here, the fit for the Milky Way follows the scaling:

$$\sigma^2 = \sqrt{\pi} R / 3.4. \quad (2)$$

It is shown that the nuclear GMAs are more turbulent for their size compared to disk GMAs of similar radii.

Using a python package created by Dr. Rosolowsky, the GMAs' positions relative to the galaxy's centre were calculated. Fig. 4 shows these galactocentric radii plotted against turbulent line width (σ_0) on a 1 pc scale, calculated with Eq. 3. Here, the distinction between nuclear and disc GMA populations is clear here, with the cut off at 1kpc from the centre.

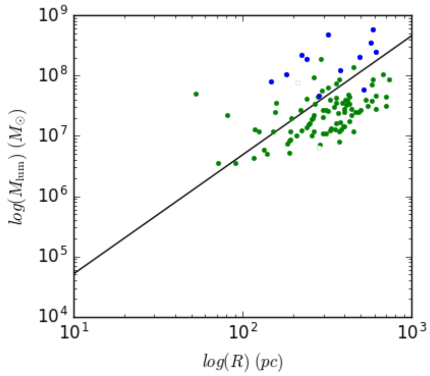

FIG. 2: Luminous mass as a function of GMA radius. Expected scaling from Eq. 1. Blue is nuclear clouds and green is disk clouds.

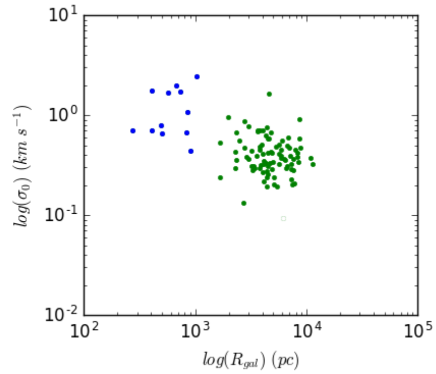

FIG. 4: Turbulent line width as a function of GMA's distance from the galactic centre. Blue is nuclear clouds and green is disk clouds.

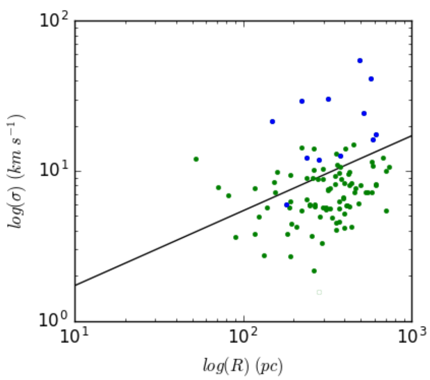

FIG. 3: Velocity dispersion as a function of GMA radius. Expected scaling from Eq. 2. Blue is nuclear clouds and green is disk clouds.

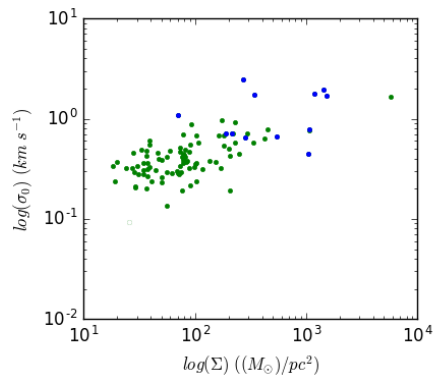

FIG. 5: Turbulent line width as a function of surface density. Blue is nuclear clouds and green is disk clouds.

$$\sigma_0 = \sigma/\sqrt{R/pc}. \tag{3}$$

Fig. 5 is a plot of turbulent line width as a function of surface density (Σ), described by Eq. 4. From Fig. 4 and Fig. 5, nuclear clouds tend to be more turbulent and dense than disk clouds.

$$\Sigma = M_{lum}/\pi R^2. \tag{4}$$

Finally, the mass distribution of the GMAs was studied and the parameters of the powerlaw fit to the data were found. The cumulative mass function (N(>M)) was found, as represented by Eq. 5 where α is the index, n_{max} is the maximum cloud mass, and N_{max} is the number of clouds near that mass.

$$N(>M) = \frac{\beta M_\odot}{\alpha+1}\left(\frac{M}{M_\odot}\right)^\alpha. \tag{5}$$

Using the python package "powerlaw", Fig. 6 was created showing the powerlaw fit for each of our populations of clouds: nuclear, disk and the combined data set. Note that we have manually set the minimum mass included in the fits of the nuclear and disk clouds to be that of the combined data $(2.7 * 10^7 (M_\odot))$.

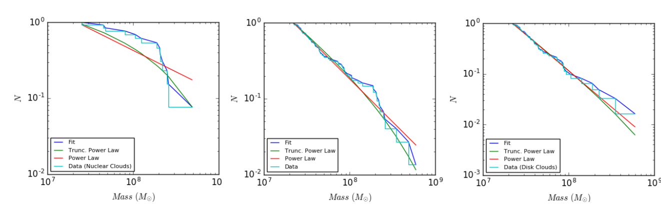

FIG. 6: Cumulative mass function of data, with plots of nuclear and disk clouds done separately as well as combined.

Table. I, presents the powerlaw index (α), the log of the likelihood ratio that the truncated or nontruncated distribution is better (R), where R being greater than zero means that the data are more consistent with the nontruncated powerlaw and R being smaller than zero means the data are more consistent with the truncated powerlaw, and the significance of the result (p), where a value close to zero means that the difference between the two distributions is significant. Rosolowsky (2005) showed that for GMCs the powerlaw index (α) varies between -2.5 to -1.5. Our results for GMAs fit in this expected range for lower mass systems.

Cloud Subset	α	R	p
All	-2.14	-1.30	0.10
Nucleus	-1.58	-3.25	0.01
Disk	-2.38	-0.35	0.4

TABLE I: Results from Fig. 6 powerlaw fit. Listed are the indices, likelihood ratios of truncated and nontruncated distributions, and result significances for total data, nuclear population and disk population treated separately.

IV. FURTHER GOALS

Having already compared the properties of the GMAs in the galactic centre with those in the disk, we are now interested in comparing spiral arm and inter-arm GMAs. Subsets will be graphically selected using Fig. 7 and the previous analysis will be redone on each subset. Identifying differences in mass distributions and turbulent properties between those populations will put us closer to understanding how GMA properties change throughout the galaxy. The final step will be looking at star formation rates within the galaxy, and how those rates change between the galaxy populations.

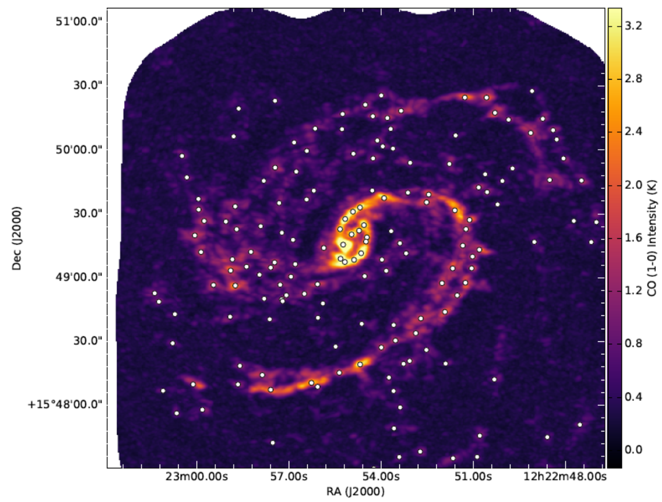

FIG. 7: Graph of GMA positions in the galaxy. Brighter regions correspond to higher CO intensity and GMA locations.

[1] E. Rosolowskys *The Mass Spectra of Giant Molecular Clouds in the Local Group*, Publications of the Astronomical Society of the Pacific, Vol. 117, No. 838 (December 2005), pp. 1403-1410.

[2] P. M. Solomon, *et al.. Mass, Luminosity, and line width relations of galactic molecular clouds*, The Astrophysical Journal Vol. 319 (August 15 1987), pp 730-741