A mean density of $120 \, M_\odot \, pc^{-3}$ for Central Molecular Zone clumps – Evidences for shear-regulated pressure equilibrium in the Galactic Center

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ABSTRACT

We carry out a systematic study of the density structure of gas in the Central Molecular Zone (CMZ) in the Galactic center by extracting clumps from the ATLASGAL 870 $\mu$m survey. We find that the clumps follow a scaling $m = \rho_0 r^3$ which corresponds to a characteristic density of $n_H = 2.5 \times 10^3 \, cm^{-3}$ ($\rho_0 = 120 \, M_\odot \, pc^{-3}$) with a variation of $\sim 1$ dex. This characteristic density can be interpreted as the result of pressure equilibrium between the molecular gas and the warm ambient ISM. Different from clumps in the Milky Way disk, self-gravity cannot compress the clumps significantly since strong shear converts gas into pressure-confined droplets which are unable to collapse. The fact that the clumps reach this shear-regulated pressure equilibrium may explain the fact that star formation in the CMZ is highly inefficient compared to the rest of the Milky Way disk. We also identify a population of clumps whose densities are two orders of magnitudes higher in the vicinity of the Sgr B2 region, which we argue are produced by the collisions between the clumps. For collisions to occur, processes such as compressive tides probably have created the appropriate condition by assembling the clumps together.

Key words: Galaxy: centre – ISM: clouds – ISM: structure – ISM: evolution – stars: formation

1 INTRODUCTION

The Central Molecular Zone (CMZ) is a disk-like gas structure that rotates around the center of the galaxy. The region has a size of $\sim 500 \, pc$, and it contains a total of $3 \times 10^7 \, M_\odot$ of molecular gas (Bally et al. 1987; Dahmen et al. 1998). The gas rotates at a speed of $\sim 200 \, km \, s^{-1}$ where the centrifugal force is balanced by gravity from the central stellar budge (Sofue 2013). Different from “ordinary” molecular clouds, gas in the CMZ is characterized by a higher degree of turbulent motion (Shetty et al. 2012). It has been found that the star formation efficiency of the CMZ is one order of magnitude lower compared to that of the Milky Way (Longmore et al. 2013; Kruĳssen et al. 2014; Barnes et al. 2017; Kauffmann et al. 2017a).

Studying the evolution of gas in the CMZ is important for two reasons: First, the fact that the gas dynamics and star formation in the CMZ are distinct from the rest of the Milky Way means that CMZ is a unique laboratory where we can deepen our understanding of the star formation process. Second, understanding the evolution of gas in the CMZ is a key to understand gas transport between the Galactic disk and the central black hole, which is intimately connected to other important questions such as black hole growth, AGN feedback, and galactic disk evolution.

A very first step towards understanding the gas evolution is to measure the density structure, which will be focused on in this paper. There has been plenty of studies characterizing the (spatial, kinematic and chemical) structure of molecular gas in the CMZ (e.g. Jones et al. 2008; Bally et al. 2010; Kruĳssen et al. 2015; Henshaw et al. 2016). However, a detailed study on the density structure of the CMZ and its evolution down to sub-pc-scale is still lacking.

In this paper, we study the density structure of the CMZ region using data from the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL; Schuller et al. 2009). ATLASGAL survey is a survey of the inner Galaxy at 870 $\mu$m performed by the APEX telescope. It has a spatial resolution...
of around 19". The survey is suitable for us since 870 μm is a wavelength suitable for tracing the cold gas. Besides, the 19" resolution translates to a scale of 0.74 pc assuming that we are ~ 8 kpc away from the CMZ, guaranteeing that the majority of the dense clumps at the CMZ region are reasonably resolved. Compared to previous surveys such as BGPS (Aguirre et al. 2011), the ATLASGAL survey has a much higher detection sensitivity (∼ 0.1 Jy beam⁻¹). Taking advantage of this, we perform a systematic study of the structure of gas in the whole CMZ region, and perform a joint analysis of the statistical properties of the gas clumps with their positions and discuss the implications on gas dynamics and star formation in the Milky Way central region.

2 OBSERVATIONS & ANALYSIS

2.1 Continuum data at 870 μm

We use 870 μm continuum data from ATLASGAL¹ survey (Schuller et al. 2009) to study the density structure of dense gas in the CMZ. The ATLASGAL results are well-suited to the study of small-scale (0.7 to 6 pc), high surface density structures (structures whose surface densities are larger than 500 M⊙pc⁻²). These arise come from the followings: One smaller scales, we are limited by our resolution, which is ~ 0.74 pc. Structures of large sizes (larger than ~ 6 pc) are filtered out due to the limitation of ground-based bolometer observations, and structures with surface densities lower than 500 M⊙pc⁻² can not be reliably detected due to our limited sensitivity (∼ 0.1 Jy beam⁻¹). We note that we might underestimate the mass of the largest (~ 3 pc) clumps by up to 50% (Mattern et al. 2018).

2.2 Clump extraction

To capture the density structure of the molecular gas and their spatial variations, we use the algorithm GAUSSCLUMPS (Stutzki & Guesten 1990; Kramer et al. 1998) in the GILDAS² software package to extract dense clumps from the

¹ The ATLASGAL project is a collaboration between the Max-Planck-Gesellschaft, the European Southern Observatory (ESO) and the Universidad de Chile.

² https://www.iram.fr/IRAMFR/GILDAS/

Figure 1. Spatial distribution of clumps of different densities. The grayscale image in the background is the 870 μm continuum emission map from the ATLASGAL survey (Schuller et al. 2009). Overlaid circles represent results from the GAUSSCLUMPS algorithm, where contours of different colors represent clumps of different densities. The densities which contours of different colors represent are indicated in the upper right.

2.3 Dust temperature estimation

To accurately estimate the clump masses it is necessary to estimate the dust temperature. Using the high-quality Hi-GAL data covering a large wavelength ranging from 70 to 500 μm (Molinari et al. 2016), we calculate the dust temperature map via fitting the spectral energy distribution (SED) survey, assuming that the flux density of each sub-source is approximated by a Gaussian distribution. This method has been successfully adopted in Zhang et al. (2018, 2019). We extract the 870 μm clumps by fitting to Gaussian shape to a well-resolved peaks with intensity I_{870μm} above 5σ (σ = 0.1 Jy beam⁻¹) with FWHM larger than 19" (870 μm beam size). The identified 1338 clumps are presented with ellipses in Figure 1, and the physical parameters are listed in Table A1.
to the multi-wavelength images on a pixel-by-pixel basis (e.g. Wang et al. 2015). This method has been successfully adopted in many works, such as Zhang et al. (2017a,b) and Zhou et al. (2019). In current work, we regridded the pixels onto the same scale of 11.5\(^\prime\), and convolved the images to the same Gaussian beam with FWHM = 45\(^\prime\) corresponding to the measured beam size of 500\(\mu\)m data. Other parameter setup is the same as that in Zhang et al. (2017b). The dust temperature \(T_{\text{dust}}\) map was made and shown in Figure A1.

### 2.4 Mass and density calculation

Assuming that the dust emission is optically thin and the gas-to-dust mass ratio is 100 (Glauser et al. 2008), we calculate the clump masses \(M_{\text{clump}}\) following Kauffmann et al. (2008) via

\[
\left( \frac{M_{\text{clump}}}{M_\odot} \right) = 0.12 \left( \frac{\nu}{14.3\text{GHz}} \right)^{\frac{1}{4}} \left( \frac{n}{10^4 \text{cm}^{-3}} \right)^{\frac{1}{4}} \times
\]

\[
\exp \left( - \frac{\lambda}{\text{cm}^{2} \text{g}^{-1}} \right) \left( \frac{S_{\nu}}{3} \right) \left( \frac{D}{\text{kpc}} \right)^2 \left( \frac{A}{\text{mm}^2} \right)^{-3},
\]

where \(\lambda = 870\mu\text{m}\) is the observational wavelength, \(T_{\text{dust}}\) is the dust temperature (see Section 2.3), \(\kappa_\nu = 0.0185 \text{cm}^2 \text{g}^{-1}\) is the dust opacity at 870\(\mu\text{m}\) (Ossenkopf & Henning 1994), \(D\) is the distance to the Sun, and integrated flux \(S_\nu\) is

\[
S_\nu = I_{\text{peak}} \times \text{FWHM}_{\text{clump}} / \text{FWHM}_{\text{obs}},
\]

where \(\text{FWHM}_{\text{clump}}\) is the extracted Gaussian size of each clump by \textsc{gaussclumps}, and \(\text{FWHM}_{\text{obs}}\) is the beam size in observations. If the cores are considered as uniform spheres, the volume density \(n_{\text{HI}}\) can be roughly estimated by \(n_{\text{HI}} = 0.12 M_{\text{clump}} / R_{\text{eff}}^2\), where \(R_{\text{eff}}\) is related to FWHM by \(R_{\text{eff}} = \text{FWHM}/(2 \sqrt{2})\). A detailed justification of this formula can be found in Appendix B. The derived parameters are listed in Table A1.

### 3 RESULTS

#### 3.1 Mass, size and density distributions

In this paper, we study the density distribution of gas on scales from ~ 0.7 to ~ 6 pc and column density \(\gtrsim 500 \, M_\odot \, \text{pc}^{-2}\), which can be reliably recovered by the ATLASGAL survey. Figure 1 plots the result of our clump extraction obtained using \textsc{gaussclumps}, where each clump is represented with an ellipse. Our source extraction have captured the majority significant structures (\(K_{\text{70um}} > 5\sigma\)) visible on the map. In total, we have recovered a mass of \(5.41 \pm 0.05 \times 10^6 \, M_\odot\), which is much larger than the mass of \(6 \times 10^5 \, M_\odot\) recovered by the BGPS survey (Bally et al. 2010) thanks to the fact that our observations have a better detection sensitivity and spatial dynamical range. However, our total mass is still smaller than that (~ 3 \(\times 10^7\) \(M_\odot\)) reported in Bally et al. (1987) and Dahmen et al. (1998) estimated using CO observations of a much lower resolution. This difference is caused by a combination of (a) they analyzed an area that is twice as large as ours (b) although our observations have significantly better angular resolutions, we are more limited by sensitivity and spatial dynamical range. The \(^{13}\text{CO}\) observations of Bally et al. (1987) allow them to probe gas with much lower surface densities (e.g. a few tens of \(M_\odot \, \text{pc}^{-2}\)), which is round 1 order of magnitude lower than our limiting surface density. Presumably, there are gas whose surface densities lie between 50 to 500 \(M_\odot \, \text{pc}^{-2}\). These gas can be detected (yet unresolved) in Bally et al. (1987) but remains undetected by ATLASGAL. Nevertheless, we do not necessarily need to recover all the gas. Figure 2 plots the distribution of clumps in the mass-size plane. Above the detection limit, the clumps have a very structured distribution. We note that the pixels which contain the largest number of clumps seem to follow a relation with \(M_{\text{clump}} \sim r^3\) which points to a constant density.

To further determine the density structure of the region, in right panel of Figure 3, we plotted the mass-weighted density distribution of groups of clumps of different sizes, from which we infer a density of \(n_{\text{HI}} \sim 2.5 \times 10^4 \text{cm}^{-3}\), \(\rho_0 \sim 120 \, M_\odot \, \text{pc}^{-3}\). Since this density is independent on the clump radius, we consider it as the characteristic density of the CMZ clumps. This characteristic density points to a mass-size relation of

\[
M_{\text{clump}}/M_\odot = 1000 \, (r/\text{pc})^3,
\]

which appears to describe our data reasonably well when over-plotted on Figure 2.

We note that the distribution of clumps in the mass-size plan is dependent on the sensitivity of our observations? To evaluate this effect, we plot the clumps with \(4\sigma > K_{\text{70um}} > 3\sigma\) and use them to mark out the parameter range where the number density of the clumps are affected by our sensitivity, which corresponds to a limiting surface density of 500 \(M_\odot \, \text{pc}^{-2}\) (see Section 2.1). Above this limit, \(m \sim r^3\) appears to be a good representation of the mass-size distribution of the clumps recovered from our observations.

#### 3.2 Spatial distribution of clumps of different densities

To further understand the overall density structure, from Figure 3, we divide the clumps into three groups: the first group of gas clumps has a gas density with \(n_{\text{HI}} < 2.7 \times 10^4 \text{cm}^{-3}\), which is called as “lower-density clumps”, the second group of gas clumps has a gas density with \(2.7 \times 10^4 > n_{\text{HI}} > 2.7 \times 10^3 \text{cm}^{-3}\), which we call “higher-density clumps”, and the third group of gas clumps has a density with \(n_{\text{HI}} \geq 2.7 \times 10^3 \text{cm}^{-3}\), which is called as “highest-density clumps”. The “highest-density clumps” seems to belong to a parameter range that is separated from the majority of the clumps, which is evident from the discontinuity in density distribution in Figure 3.

We then plot the spatial distributions of clumps of different densities in Figure 1. It emerges that the spatial distribution of the higher-density clumps exhibits a pattern where they seem to follow an arc-like structure which stretches from \(l = 1^\circ\) to \(l = -1^\circ\), and it contains some of the most active star-forming regions in the CMZ like the Sgr B2. To some extent, one can relate our dense arc with the 100-pc twisted ring identified by Molinari et al. (2011), where dense gas (gas with densities above \(n_{\text{HI}} \approx 2.7 \times 10^4 \text{cm}^{-3}\)) forms a coherent, twisted pattern, and we note that gas is unevenly distributed along this ring, with clumps of the highest densities where \(n_{\text{HI}} \geq 2.7 \times 10^3 \text{cm}^{-3}\) distribute mostly within the vicinity of the Sgr B2 region. This uneven distribution of dense gas implies that the dynamics of the region is non-stationary.
as expected from some recent models (Kruijssen et al. 2015; Henshaw et al. 2016; Sormani et al. 2018).

4 DISCUSSIONS

4.1 A characteristic density of $120 M_\odot$ pc$^{-3}$ for the majority of the clumps – evidences for shear-regulated pressure equilibrium

We remind the reader that in the Milky Way, the cold molecular gas establishes a pressure equilibrium with the warm phases of the ISM (Spitzer & Tomasko 1968; Field et al. 1969). The pressure equilibrium allows us to estimate the density of molecular gas, and this density is indeed close to the mean density of the molecular gas in the bulk of the Milky Way disk.

However, the density variation we observed in the CMZ is much smaller than the density variation observed in the Milky Way disk. A major reason for this is that self-gravity is dynamically important. For example, in the Milky Way clumps, the masses and sizes are related by $m \sim r^{1.67}$ (e.g. Urquhart et al. 2013; Pfalzner et al. 2016; Li 2017a; Zhang & Li 2017), where clumps of different sizes have different densities. But in the CMZ, the clump density appears to be independent on the clump size. This reflects the uniqueness of the CMZ in terms of density structure.

4.1.1 Evidences of pressure equilibrium

We propose that this almost-constant gas density observed in the CMZ region can be explained by the pressure equilibrium. The gas temperature is found to be around $50-100$ K (Nagai et al. 2007; Ao et al. 2013; Ginsburg et al. 2016). Assuming a gas temperature of $70$ K, we estimate that the cold gas has a pressure of

$$p_{\text{gas}} = T_{\text{gas}} \rho_{\text{gas}} \approx 3.5 \times 10^3 \text{ K cm}^{-3},$$

where $k_B$ is the Boltzmann constant.

As a comparison, using temperature measured by Yamauchi et al. (1990), Spergel & Blitz (1992) estimated a pressure of

$$p_{\text{gas}} \approx 10^3 - 10^4 \text{ cm}^{-3},$$

for the warm ambient gas. The result is confirmed by later measurements (e.g. Muno et al. 2004). Since $p_{\text{external}} \approx p_{\text{external}}$, pressure equilibrium does provide a good explanation to the observed gas density.

We still observe a density fluctuation of around $\sim 1$ dex, which can be caused by processes such as turbulence. Turbulence is known to be capable of producing density variations (Vazquez-Semadeni 1994; Padoan et al. 1997; Scalo et al. 1998; Federrath et al. 2010). The clumps we observed have a (density-weighted) density variation of $\sim 1$ dex. Adopting the results from Konstandin et al. (2012), this can be produced by a turbulence of $M = 10$ where $M$ is the Mach number, which agrees with the measured Mach number by Henshaw et al. (2016). Turbulence can produce the observed density variations.

4.1.2 Regulation of collapse by shear

Compared to the Milky Way clouds, the clumps in the CMZ share a density that is almost completely independent on the clump radius. In the CMZ, we propose that it is the pressure equilibrium that determines the density of the clumps. This has become possible in the CMZ since shear is strong enough to counteract against gravity in clumps.

We remind the readers that in the absence of shear, self-gravity is dynamically important for these clumps. We first estimate the pressure caused by gravity, which is

$$P_{\text{grav}} = \frac{G \Sigma_{\text{clump}}}{k_B} = \frac{G \rho_{\text{clump}}}{k_B} = 10^6 \text{ K cm}^{-3} r_{\text{clump}}^2 \text{ pc}^{-2},$$

where $r_{\text{clump}}$ is the size of a clump. For a typical clump of size $\sim 1$ pc, this pressure is indeed comparable to the internal and external pressure we estimated before.

Although gravity should be strong, in the CMZ, its effect is largely canceled by effects like shear and extensive tidal force. Shear can cause gas different radii to rotate at different angular speeds, and this differential motion stretches gas into long streams before they can collapse on their own. Tidal force causes different parts of a clump to accelerate
differently, and it can halt the fragmentation when the tidal force is extensive.

The fact that gas clumps organize into streams (e.g. Henshaw et al. 2016) indicates that shear should be dynamically important. To evaluate the relative importance between shear and self-gravity, we compute shear timescale and compare it with the free-fall time. Assuming that the rotation curve of the CMZ gas can be parameterized as \( v \sim r^\alpha \), the shear time is

\[
\tau_{\text{shear}} = \left( \frac{\partial v}{\partial r} \right)^{-1} = \frac{1}{1-\rho} \Omega^{-1} \approx 1.1 \times \Omega^{-1} \approx 0.9 \text{ Myr}, \quad (7)
\]

where, to estimate the value of \( \rho \), we have used the mass profile used in Krumholz & Kuijssen (2015) where \( m \sim r^{2.3} \), such that \( p = 0.6 \), and \( \Omega = \sqrt{v/r} \) is estimated assuming \( v = 130 \text{ km s}^{-1} \) and \( r = 150 \text{pc} \) (e.g. Krujissen et al. 2015).

For comparison, the timescale for gravitational collapse to occur on a uniform sphere is

\[
\tau_g = \sqrt{\frac{3\pi}{32G\rho_{\text{gas}}}} \approx 0.54 \times \frac{1}{G\rho_{\text{gas}}} \approx 0.8 \text{ Myr}. \quad (8)
\]

Since the shear time is comparable to the free-fall time, shear is able to counteract against gravitational collapse. We must acknowledge that the both the shear timescale and the free-fall timescale estimates are accurate only in the order-of-magnitude sense. Since the rotation curve of the CMZ, however, is still uncertain (e.g. Sofue 2013; Krumholz & Kuijssen 2015). The dust-to-gas ratio of CMZ might be higher in the CMZ (e.g. as discussed in Longmore et al. 2013).

Our findings provide crucial insights into the puzzle of the inefficiency of star formation in the CMZ region. It has been believed that enhanced turbulence can explain the inefficiency of star formation (Krujissen et al. 2014). Here, our analyses have revealed that in the CMZ region, shear has the adequate strength to halt the collapse of individual clumps. Our results agrees with earlier proposals that shear can be a factor to regulate collapse of the CMZ (e.g. Longmore et al. 2013; Emsellem et al. 2015; Krumholz & Kuijssen 2015; Jeffreson et al. 2018), although in those papers shear is expected to halt the collapse of the CMZ on the large scale, whereas in our case, the importance of shear is even more pronounced where it can halt the collapse of the individual clumps, although other processes such as turbulence can also be important.

4.2 Forming dense gas through clump collisions

Although only a small fraction of the gas is contained in densest clumps (\( n_{\text{H}_2} \geq 2.7 \times 10^4 \text{cm}^{-3} \)), they are associated with the majority of star formation found in this region (see, e.g., the star formation rate inferred from Kauffmann et al. 2017b).

The spatial distribution of clumps of different densities are plotted in Figure 1, where it is clear that clumps with \( n_{\text{H}_2} > 2.7 \times 10^4 \text{cm}^{-3} \) (the “highest density component”) are mostly distributed within the vicinity of the Sgr B2 region. The density of this component is two orders of magnitudes higher than the mean density of gas in the CMZ.

How to produce this “densest component”? Gravitational collapse is certainly capable of producing gas of higher densities. However, if an ensemble of gas clouds are allowed to collapse freely, we expect to observe a smooth density distribution where the amount of high-density gas is relatively small compared to the amount of low-density gas (Kritsuk et al. 2011; Girichidis et al. 2014; Li 2018). In contrast to this, there appears to be an excess of gas of highest density (\( n_{\text{H}_2} \geq 2.7 \times 10^4 \text{cm}^{-3} \)), which can be seen from the middle and right panel of Figure 3 where we plotted the mass-weighted gas densities.

We propose that the excess amount of dense clumps are produced by collisions between the clumps. Collision between clouds is a process believed to have occurred in the Milky Way disk (Tasker & Tan 2009; Torii et al. 2011; Fukui et al. 2014; Gong et al. 2017). Dobbs et al. (2011), Li (2017b), and Donkov & Stefanov (2019) estimated the timescale for such processes to occur, and found that the collision time is comparable to the dynamical time in the bulk of the Milky Way disk. This scenario is feasible since (a) clump collisions should occur in this region on a regular basis, and (b) these collisions are capable producing clumps of such high densities.

To evaluate whether cloud-cloud collisions should occur near Sgr B2, redating the mean free path can be estimated as (Li 2017b)

\[
\lambda_{\text{clamp}} \approx \frac{\Sigma_{\text{clamp}}}{\rho_{\text{mean}}} = \frac{120 M_\odot \text{ pc}^{-2}}{1000 M_\odot \text{ pc}^{-3}} \approx 0.12 \text{ pc}, \quad (9)
\]

where, to estimate the mean surface density of the clumps, we have adopted a mean density of \( n_{\text{H}_2} = 2 \times 10^4 \text{cm}^{-3} \) and a typical size of 1 pc (see Figure 1), such that \( \Sigma_{\text{clamp}} = 120 M_\odot \text{ pc}^{-2} \) and the Sgr B2 region is estimated to have a mean density of \( \approx 1000 M_\odot \text{ pc}^{-3} \). The mean free path of clumps in the region is around 0.12 pc, which is much smaller than the size of the region. If the clumps in the CMZ are not collapsing by themselves, when assembled to a very small region, collisions should occur.

Can collisions between clumps produce those highest-density clumps? In the region close to Sgr B2, the density enhancement due to collisions can be estimated as \( \rho' / \rho \approx M / (v_{\text{collide}}/c_s)^2 \) where \( \rho' / \rho \) is the density contrast. To produce a density enhancement of 100, one needs the clumps to collide at Mach number \( M = 10 \). Assuming a sound speed of 1 km s\(^{-1}\), the cloud must collide with a relative speed of 10 km s\(^{-1}\), which is possible given that an inter-clump velocity dispersion of a few tens of km s\(^{-1}\) is common at the CMZ region (Henshaw et al. 2016). Our mechanism of producing dense clumps through collisions is consistent with the result of Tsuboi et al. (2015) where they found enhancements of SiO emission lines in the vicinity of the Sgr B2 complex, which they interpreted as the result of shocks produced during clump collisions.

Recent papers have pointed out that the importance of processes such as changes of shear, compressive tidal fields in triggering star formation (Krumholz & Kuijssen 2015; Jeffreson et al. 2018; Dale et al. 2019; Kuijssen et al. 2019). We agree with them that these physical mechanisms can play important roles in determining the overall star formation. However, we point out that the picture we have in mind is very different: in models such as Dale et al. (2019), when a cloud passes through certain locations, tidal compression is imposed on the cloud as a whole which causes it to collapse, whereas in our case (similar to Li 2017b), an external compression (presumably caused by the tidal effects) cause ensembles of clumps collide and agglomerate, through
which dense gas is produced and star formation is triggered. The collisions also lead to the formation of clumps of higher masses. The difference between two difference cases is illustrated in Figure 4.

5 CONCLUSION

Using data from the ATLASGAL survey, we study the density structure of the molecular gas in the CMZ region traced by dust continuum emission. We have extracted 1338 clumps from the data, and study the properties of the extracted clumps in terms of mass, size and density. We find that the majority of the clumps follow $m \sim r^3$, which points to a characteristic density $\rho_c = 2.5 \times 10^4 \text{ cm}^{-3}$. We also identified an over-abundance of clumps with $n_H > 2.7 \times 10^5 \text{ cm}^{-3}$ in the vicinity of the Sgr B2 region. We propose that they are produced by agglomerations and collisions of clumps of lower densities. For collisions to occur, processes such as tidal compression have probably provided the appropriate condition by assembling the clumps together.

Our analyses reveal that the gas in the CMZ belongs to a unique regime where shear is strong to overcome gravity in the individual clumps, such that the density of these clumps is determined directly by pressure equilibrium with the ambient environment. Our picture can be applied to study the evolution of gas at centers of other galaxies where star formation appears to be inefficient.

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REFERENCES

Aguirre J. E., et al., 2011, ApJS, 192, 4
Ao Y., et al., 2013, A&A, 550, A135
Bally J., Stark A. A., Wilson R. W., Henkel C., 1987, ApJS, 65, 13
Bally J., et al., 2010, ApJ, 721, 137
Barnes A. T., Longmore S. N., Batterby C., Bally J., Kruijssen J. M. D., Henshaw J. D., Walker D. L., 2017, MNRAS, 469, 2263
Dahmen G., Huttemeister S., Wilson T. L., Mauersberger R., 1998, A&A, 331, 959
Dale J. E., Kruijssen J. M. D., Longmore S. N., 2019, MNRAS, 486, 3307
Dobbs C. L., Burkert A., Pringle J. E., 2011, MNRAS, 413, 2935
Donkov S., Stefanov I., 2019, MNRAS, 485, 3224
Emel’ev E., Renaud F., Bournaud F., Elmegreen B., Combes F., Gabor J. M., 2015, MNRAS, 446, 2468
Federrath C., Roman-Duval J., Klessen R. S., Schmidt W., Mac Low M.-M., 2010, A&A, 512, A81
Field G. B., Goldsmith D. W., Habing H. J., 1969, ApJ, 155, L149
Fukui Y., et al., 2014, ApJ, 780, 36
Ginsburg A., et al., 2016, A&A, 586, A50
Girichidis P., Konstandin L., Whitworth A. P., Klessen R. S., 2014, ApJ, 781, 91
Glauser A. M., Ménard F., Pinte C., Duchêne G., Güdel M., Monin J.-L., Padgett D. L., 2008, A&A, 485, 531
Gong Y., et al., 2017, ApJ, 835, L14
Henshaw J. D., et al., 2016, MNRAS, 457, 2675
Jeffreson S. M. R., Kruijssen J. M. D., Krumholz M. R., Longmore S. N., 2018, MNRAS, 478, 3380
Jones P. A., et al., 2008, MNRAS, 386, 117
Kauffmann J., Bertoldi F., Bourke T. L., Evans II N. J., Lee C. W., 2008, A&A, 487, 993
Kauffmann J., Pillai T., Zhang Q., Menten K. M., Goldsmith P. F., Lu X., Guzmán A. E., 2017a, A&A, 603, A89

$m_{\text{clump}} \sim r_{\text{clump}}^3$ seems to indicate that the role of shear is indispensable.

We also identified an over-abundance of clumps with $n_H > 2.7 \times 10^5 \text{ cm}^{-3}$ in the vicinity of the Sgr B2 region. We propose that they are produced by agglomerations and collisions of clumps of lower densities. For collisions to occur, processes such as tidal compression have probably provided the appropriate condition by assembling the clumps together.

Our analyses reveal that the gas in the CMZ belongs to a unique regime where shear is strong to overcome gravity in the individual clumps, such that the density of these clumps is determined directly by pressure equilibrium with the ambient environment. Our picture can be applied to study the evolution of gas at centers of other galaxies where star formation appears to be inefficient.
APPENDIX A: TEMPERATURE MAP

In Figure A1 we present the map of dust temperature. See Section 2 for details.

APPENDIX B: ESTIMATION OF CLUMP DENSITY

A crucial step in our analysis is to estimate the density of the clumps. Ideally for a clump of constant density, its density can be estimated using

\[
\rho_\text{clump} = \frac{m_\text{clump}}{4/3 \pi r_0^3} . \tag{B1}
\]

where \( r_0 \) is the clump radius and \( m_0 \) is the mass. However, in our analysis, due to the limitations from observations as well as our clump extraction algorithm, both \( m_\text{clump} \) and \( r_\text{clump} \) might have some biases. To access these effect, we have performed a simulation where we created a clump of constant density in 3D, projected it to 2D, and computed the masses and sizes of the simulated clump. Assuming that the original clump has a mass of \( m_{3D} \) and size of \( r_{3D} \), the extracted clump from our simulation has a mass of \( m_\text{clump} \) and a size of \( r_\text{clump} \), we find

\[
m_\text{clump} = 0.76 \times m_{3D} , \tag{B2}
\]

and

\[
r_\text{clump} = 0.72 \times r_{3D} . \tag{B3}
\]

Given these facts, to accurately compute the clump density, we propose to use the equation

\[
\rho_\text{clump} = 0.12 \times m_\text{clump} r_\text{clump}^{-3} , \tag{B4}
\]

such that \( \rho_{3D} = m_{3D}/(4/3 \pi r_0^3) \) is guaranteed.
Figure A1. Dust temperature via fitting the SED to the multi-wavelength images on a pixel-by-pixel basis using the high-quality Herschel data covering a large wavelength range from 70 to 500μm.

Table A1. Parameters of identified Gaussian clumps.

| Clumps No. | Offset "", "" | FWHM "" | R_{eff} pc | T_{dust} K | \(I_{670}\mu m\) Jy beam\(^{-1}\) | \(S_{670}\mu m\) Jy | \(M_{HI}\) 10\(^3\)\(M_\odot\) | \(N_{HI}\) 10\(^2\)cm\(^{-2}\) | \(n_\odot\) 10\(^3\)cm\(^{-3}\) |
|------------|---------------|----------|------------|-----------|-----------------|----------------|----------------|----------------|----------------|
| 1 | (2435.5, −96.5) | 29.1 | 0.68 | 23.6 ± 2.4 | 139.82 | 331.45 | 92.2 ± 12.8 | 50.2 ± 7.0 | 7.1 ± 1.0 |
| 2 | (2393.5, −120.3) | 34.1 | 0.80 | 24.3 ± 2.4 | 127.47 | 405.40 | 108.2 ± 14.9 | 42.7 ± 5.9 | 5.2 ± 0.7 |
| 3 | (2356.1, −146.3) | 42.3 | 0.99 | 23.0 ± 2.3 | 46.17 | 266.51 | 76.7 ± 10.8 | 19.7 ± 2.8 | 1.9 ± 0.3 |
| 4 | (2400.2, −73.0) | 42.0 | 0.98 | 21.2 ± 2.1 | 31.21 | 217.11 | 70.0 ± 10.1 | 18.3 ± 2.6 | 1.8 ± 0.3 |
| 5 | (2492.3, −96.5) | 71.2 | 1.66 | 19.9 ± 2.0 | 21.92 | 325.87 | 115.1 ± 16.9 | 10.5 ± 1.5 | 0.6 ± 0.1 |
| 6 | (2319.4, −182.3) | 52.2 | 1.22 | 20.7 ± 2.1 | 15.89 | 136.04 | 45.5 ± 6.6 | 7.7 ± 1.1 | 0.6 ± 0.1 |
| 7 | (−478.9, −296.6) | 58.8 | 1.37 | 18.7 ± 1.9 | 10.82 | 130.77 | 50.9 ± 7.7 | 6.8 ± 1.0 | 0.5 ± 0.1 |
| 8 | (−1383.7, −873.8) | 32.5 | 0.76 | 21.9 ± 2.2 | 11.09 | 32.06 | 9.9 ± 1.4 | 4.3 ± 0.6 | 0.5 ± 0.1 |
| 9 | (2430.2, −20.4) | 68.5 | 1.60 | 18.8 ± 1.9 | 10.59 | 141.79 | 54.7 ± 8.2 | 5.4 ± 0.8 | 0.3 ± 0.0 |
| 10 | (2266.2, −217.6) | 69.6 | 1.62 | 19.9 ± 2.0 | 10.28 | 142.13 | 50.2 ± 7.4 | 4.8 ± 0.7 | 0.3 ± 0.0 |
| 11 | (1716.9, −21.0) | 56.2 | 1.31 | 18.2 ± 1.8 | 9.39 | 85.19 | 34.4 ± 5.2 | 5.0 ± 0.8 | 0.4 ± 0.1 |
| 12 | (2434.2, −142.1) | 27.4 | 0.64 | 25.1 ± 2.5 | 10.38 | 50.04 | 12.8 ± 1.7 | 7.8 ± 1.1 | 1.2 ± 0.2 |
| 13 | (2353.4, −53.1) | 41.5 | 0.97 | 19.4 ± 1.9 | 8.48 | 55.79 | 20.6 ± 3.1 | 5.5 ± 0.8 | 0.5 ± 0.1 |
| 14 | (−2012.8, −375.7) | 40.9 | 0.95 | 21.5 ± 2.2 | 8.00 | 39.85 | 12.6 ± 1.8 | 3.5 ± 0.5 | 0.4 ± 0.1 |
| 15 | (−205.0, −163.6) | 63.7 | 1.48 | 36.2 ± 3.6 | 7.86 | 92.55 | 14.6 ± 1.8 | 1.7 ± 0.2 | 0.1 ± 0.0 |
| 16 | (−382.4, −253.1) | 74.8 | 1.74 | 19.2 ± 1.9 | 7.74 | 125.52 | 47.0 ± 7.0 | 3.9 ± 0.6 | 0.2 ± 0.0 |
| 17 | (918.6, 57.9) | 70.5 | 1.64 | 19.7 ± 2.0 | 6.93 | 153.58 | 55.4 ± 8.2 | 5.1 ± 0.8 | 0.3 ± 0.0 |
| 18 | (2383.2, −160.8) | 24.4 | 0.57 | 24.0 ± 2.4 | 7.84 | 16.18 | 4.4 ± 0.6 | 3.4 ± 0.5 | 0.6 ± 0.1 |
| 19 | (−89.8, −254.4) | 86.3 | 2.01 | 23.2 ± 2.3 | 6.30 | 158.23 | 45.1 ± 6.3 | 2.8 ± 0.4 | 0.1 ± 0.0 |
| 20 | (1353.0, 147.6) | 31.3 | 0.73 | 22.7 ± 2.3 | 5.95 | 15.92 | 4.7 ± 0.7 | 2.2 ± 0.3 | 0.3 ± 0.0 |
| 21 | (2453.5, −64.3) | 24.3 | 0.57 | 19.9 ± 2.0 | 8.22 | 16.13 | 5.7 ± 0.8 | 4.5 ± 0.7 | 0.8 ± 0.1 |
| 22 | (4051.9, −389.9) | 38.9 | 0.90 | 24.0 ± 2.4 | 5.32 | 24.77 | 6.7 ± 0.9 | 2.1 ± 0.3 | 0.2 ± 0.0 |
| 23 | (1776.9, 65.4) | 61.1 | 1.42 | 19.0 ± 1.9 | 5.19 | 59.08 | 22.4 ± 3.3 | 2.8 ± 0.4 | 0.2 ± 0.0 |
| 24 | (481.1, −67.5) | 62.6 | 1.46 | 27.6 ± 2.8 | 5.08 | 55.54 | 12.4 ± 1.7 | 1.5 ± 0.2 | 0.1 ± 0.0 |
| 25 | (−547.5, −262.1) | 63.0 | 1.47 | 19.8 ± 2.0 | 5.23 | 56.35 | 20.1 ± 3.0 | 2.3 ± 0.3 | 0.2 ± 0.0 |
| 26 | (−5545.6, −1412.5) | 31.9 | 0.74 | 18.9 ± 1.9 | 5.16 | 14.60 | 5.6 ± 0.8 | 2.5 ± 0.4 | 0.3 ± 0.0 |
| 27 | (−413.4, −352.5) | 69.3 | 1.61 | 20.3 ± 2.0 | 5.14 | 114.21 | 39.4 ± 5.8 | 3.8 ± 0.6 | 0.2 ± 0.0 |
| 28 | (−286.0, −233.2) | 86.6 | 2.02 | 22.1 ± 2.2 | 5.13 | 106.00 | 32.2 ± 4.6 | 2.0 ± 0.3 | 0.1 ± 0.0 |

Others are listed only in online table.