The role of the Galactic potential in shaping the structure and kinematics of the CMZ clouds

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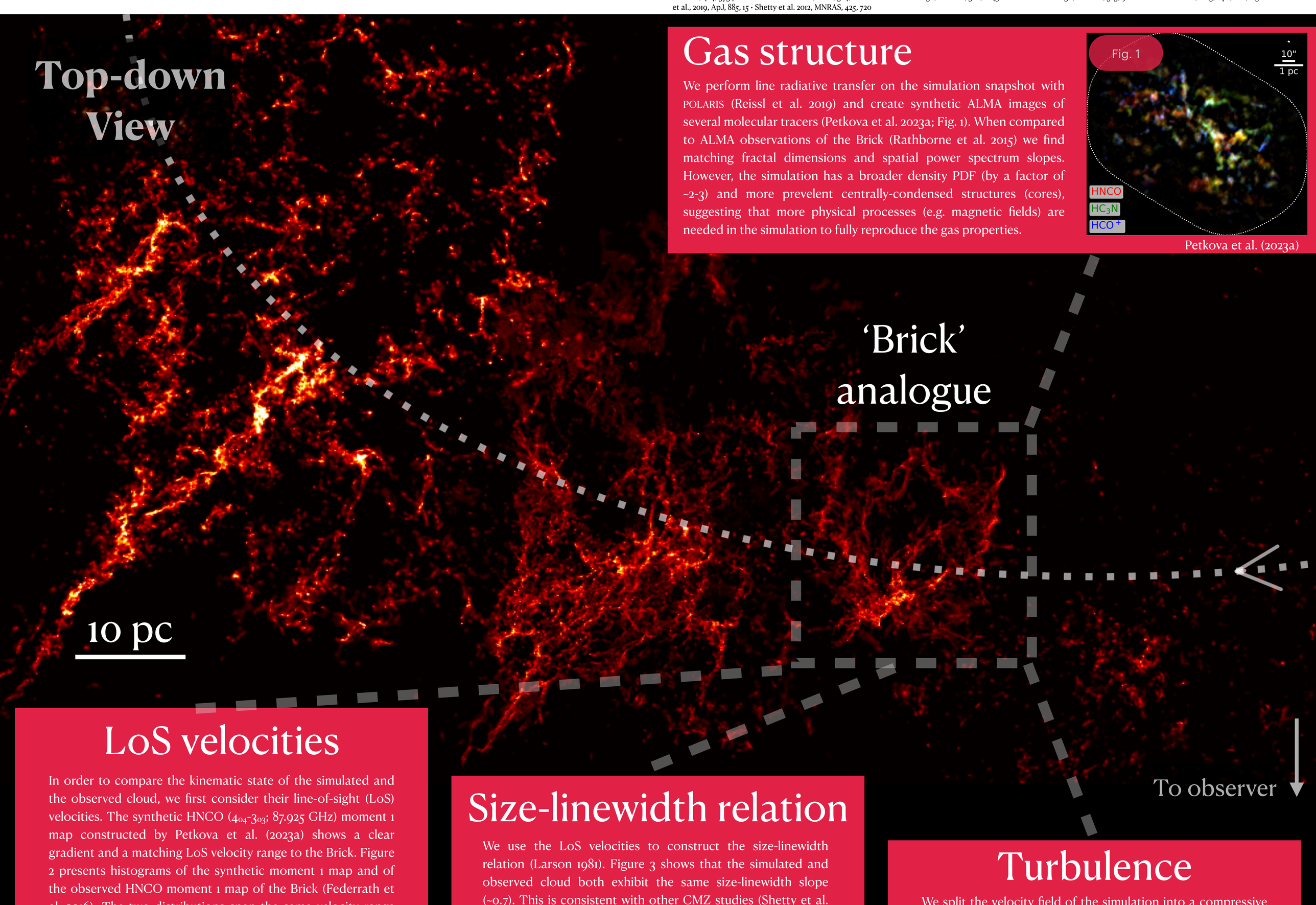
Abstract

The Central Molecular Zone (CMZ; the central ~ 500 pc of the Milky Way) hosts molecular clouds in an extreme environment of strong shear, high gas pressure and density, and complex chemistry. While the CMZ region contains a large reservoir of dense gas, it is forming stars at a rate much lower than theoretical predictions. In this work we compare the properties of hydrodynamical simulations of CMZ clouds to those of ALMA observations, with a focus on G0.253+0.016 ('the Brick'). For this comparison, we post-process the simulations and create synthetic ALMA maps of molecular line emission. We characterise the **gas structure** of the observed and simulated cloud using the density PDF, spatial power spectrum, fractal dimension, and moments of inertia. While we see good agreement in some of these, there are also key differences which we attribute to the omission of magnetic fields in the simulations. Additionally, we find excellent agreement in the kinematics of the simulated and the observed data in terms of the **line-of-sight velocity distribution**, the **size-linewidth relation**, and the predominantly **solenoidal nature of the turbulence**. Within the simulation, these properties result from the Galactic shear in combination with the cloud's gravitational collapse. This is a strong indication that the Galactic gravitational potential plays a crucial role in shaping the CMZ gas kinematics, and is a major contributor to suppressing the star formation rate by inducing predominantly solenoidal turbulent modes.

Simulations

We use the high-density (HDens) tidally-virialised cloud-scale simulation from Dale et al. (2019). Kruijssen et al. (2019) and Petkova et al. (2023a, 2023b) selected this particular model to represent the Brick as it best matches the properties of the cloud (i.e. size, column density and mass). The simulation is performed with the smoothed particle hydrodynamics (**SPH**) code GANDALF (Hubber et al. 2018). The simulation is three-dimensional, unmagnetised, and assumes an **isothermal** equation of state with a temperature 65 K. **Self-gravity** of the gas is included, whereas the field stars are included in the **background potential** (Launhardt 2002). The cloud is initialised as a sphere with total mass 4.5 x 10^5 M and 10^6 SPH particles, which is evolved on an **eccentric orbit** around the Galactic Centre. The cloud starts 0.41 Myr before the pericentre passage in the gravitational potential described in Kruijssen et al. (2015). Since no turbulence driving is included, the initial turbulent velocity field of the cloud is quickly dissipated (on a timescale ~0.56 Myr; Kruijssen et al. 2019). Turbulence is generated during the simulation through gravitational collapse and shearing motions. For our analysis we focus on the snapshot that corresponds to the present-day location of the Brick.

References: • Dale et al. 2019, MNRAS, 486, 3307 • Federrath et al. 2011, Phys. Rev. Lett., 107, 114504 • Federrath et al. 2016, ApJ, 832,143 • Henshaw et al. 2019, MNRAS, 485, 2457 • Henshaw et al. 2020, Nat. Astr., 4, 1064 • Hubber et al. 2018, MNRAS, 473, 1603 • Kauffmann et al. 2017, A&A, 603, A89 • Kruijssen et al. 2015, MNRAS, 447, 1059 • Kruijssen et al. 2019, MNRAS, 484, 5734 • Launhardt et al. 2002, A&A, 384, 112 • Petkova et al. 2023a, MNRAS, 520, 2245 • Petkova et al. 2023b, MNRAS, 525, 962 • Rathborne et al., 2015, ApJ, 802, 125 • Reissl et al., 2019, ApJ, 885, 15 • Shetty et al. 2012, MNRAS, 425, 720



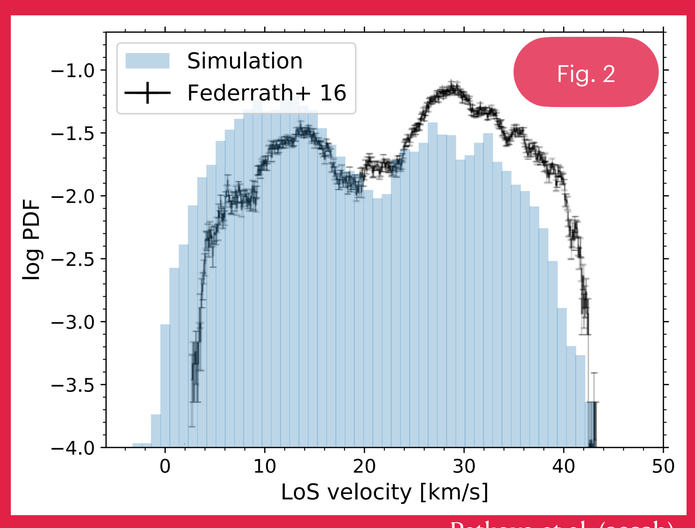
Gas structure

We perform line radiative transfer on the simulation snapshot with POLARIS (Reissl et al. 2019) and create synthetic ALMA images of several molecular tracers (Petkova et al. 2023a; Fig. 1). When compared to ALMA observations of the Brick (Rathborne et al. 2015) we find matching fractal dimensions and spatial power spectrum slopes. However, the simulation has a broader density PDF (by a factor of ~2-3) and more prevelent centrally-condensed structures (cores), suggesting that more physical processes (e.g. magnetic fields) are needed in the simulation to fully reproduce the gas properties.

Petkova et al. (2023a)

LoS velocities

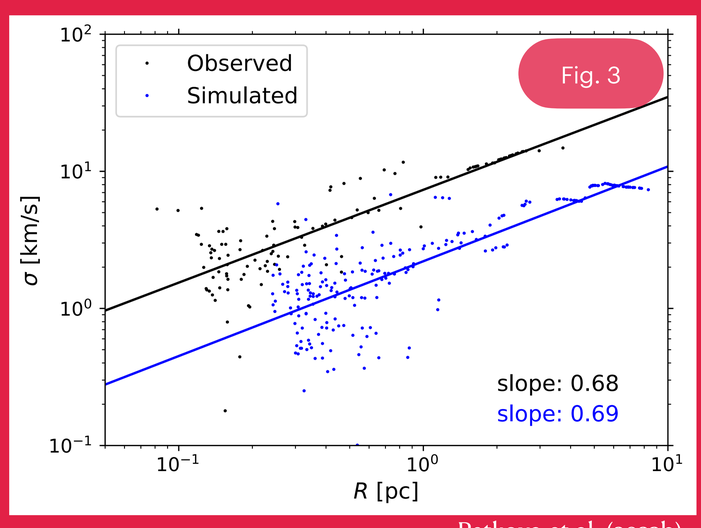
In order to compare the kinematic state of the simulated and the observed cloud, we first consider their line-of-sight (LoS) velocities. The synthetic HNCO (4_{04}-3_{03}; 87.925 GHz) moment 1 map constructed by Petkova et al. (2023a) shows a clear gradient and a matching LoS velocity range to the Brick. Figure 2 presents histograms of the synthetic moment 1 map and of the observed HNCO moment 1 map of the Brick (Federrath et al. 2016). The two distributions span the same velocity range and have a double-peaked profile, with a minimum at ~20 km s^{-1}. This velocity profile is indicative of rotation along an axis perpendicular to the line-of-sight. However, the rotation is not necessarily global but it may be present in multiple structures within the Brick which are overlapping along the LoS (Henshaw et al. 2019). This is consistent with the velocity structure of the simulation, where the rotation is multi-axial, and broken down into spatially-coherent regions.



Petkova et al. (2023b)

Size-linewidth relation

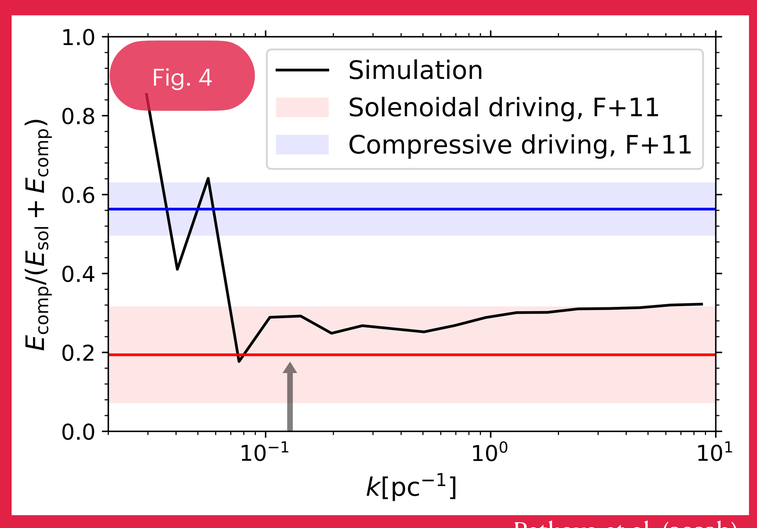
We use the LoS velocities to construct the size-linewidth relation (Larson 1981). Figure 3 shows that the simulated and observed cloud both exhibit the same size-linewidth slope (~0.7). This is consistent with other CMZ studies (Shetty et al. 2012; Kauffmann et al. 2017), but is steeper than in the Solar neighbourhood (0.5; Heyer et al. 2015). Our analysis follows the procedure of (Shetty et al. 2012), which identifies structures in position-position-velocity space with a dendrogram. In contrast, (Henshaw et al. 2020) performed a Gaussian decomposition of HNCO emission lines, and found a much shallower size-linewidth slope within identified sub-structures of the Brick. This suggests that the steeper relation may be due to rotational motions on the cloud scale.



Petkova et al. (2023b)

Turbulence

We split the velocity field of the simulation into a compressive (curl-free) and a solenoidal (divergence-free) component using Helmholtz decomposition. Figure 4 shows the compressive ratio of the simulation as a function of spatial scale (k), compared to the results of (Federrath et al. 2011) for a Mach number of ~11. For most spatial scales our simulation has a cmpressive ratio of 0.2-0.3, which is consistent with having predominantly solenoidal turbulence driving. This is also in agreement with the results of Federrath et al. (2016) for the Brick.



Petkova et al. (2023b)