Astrophysical Masers:
Unlocking the Mysteries of the Universe
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How maser observations unravel the gas motions in the Galactic Center

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Abstract. The Central Molecular Zone (CMZ), the inner 450 pc of our Galaxy, is an exceptional region where the volume and column densities, gas temperatures, velocity dispersions, etc. are much higher than in the Galactic plane. It has been suggested that the formation of stars and clusters in this area is related to the orbital dynamics of the gas. The complex kinematic structure of the molecular gas was revealed by spectral line observations. However, these results are limited to the line-of-sight-velocities. To fully understand the motions of the gas within the CMZ, we have to know its location in 6D space (3D location + 3D motion). Recent orbital models have tried to explain the inflow of gas towards and its kinematics within this region. With parallax and proper motion measurements of masers in the CMZ we can discriminate among these models and constrain how our Galactic Center is fed with gas.

Keywords. masers, instrumentation: interferometers, astrometry, Galaxy: center, Galaxy: kinematics and dynamics, radio lines: ISM

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1. The Central Molecular Zone

The Central Molecular Zone (CMZ), the inner ∼450 pc of the Milky Way, produces 5−10% of the infrared and Lyman continuum luminosity of our Galaxy and 10% of the Galaxy's total molecular gas are located here (Morris & Serabyn 1996 and references therein). The conditions are extreme: high average densities ($>10^4$ cm^{-3}), high gas temperatures (>60 K), large velocity dispersions ($>$ 15 km s^{-1}), etc. (Morris & Serabyn 1996 and references therein for all above quantities).

Several groups have suggested that the formation of stars and clusters is closely linked with the orbital dynamics of the gas (e.g. Molinari *et al.* 2011, Longmore *et al.* 2013, Kruijssen *et al.* 2015). The orbital motion of giant molecular clouds in the CMZ has been studied for decades (e.g. Bally *et al.* 1988, Sofue 1995, Tsuboi *et al.* 1999, Oka *et al.* 1998). Spectral line observations of the molecular gas in this region show a complex kinematic structure in position-position-velocity space. Most of the gas seems to be located in two coherent gas streams, covering a large range of line-of-sight velocities. However, there are several difficulties with this observational approach and its interpretation. Due to our position in the Galactic plane, we see foreground and CMZ clouds in projection and

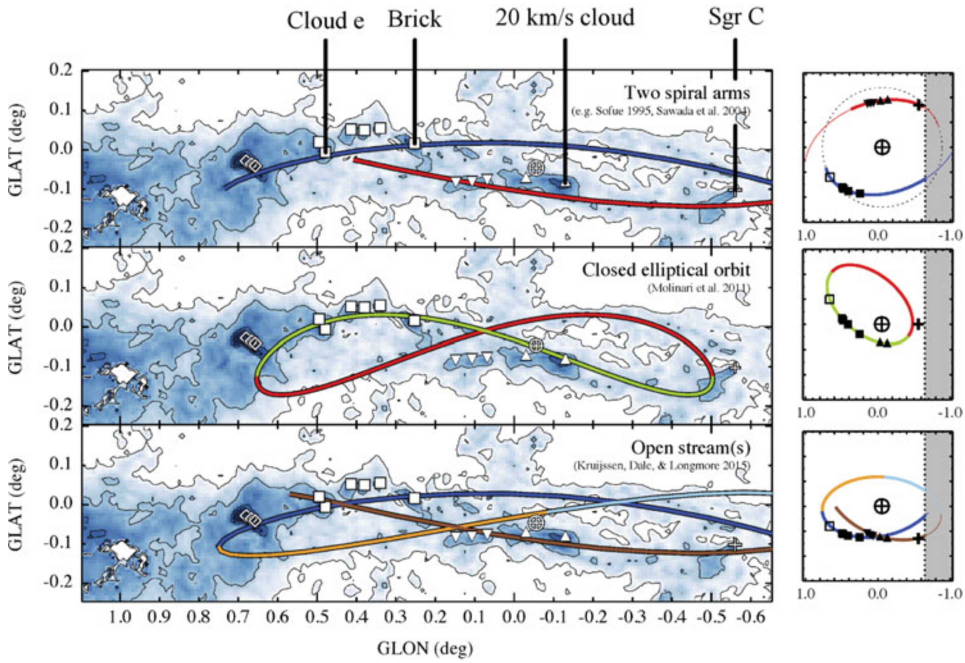

Figure 1. Left: Projected view of the gas orbits predicted by the three models discussed in Section 2 overlaid on a Herschel-derived molecular hydrogen column density map by Battersby *et al.* (in prep.). Right: Top-down view of the same orbits (motion in clockwise direction). The symbols mark important positions along the orbits: Sgr C (plus), 20 and 50 km s^{-1} cloud (upward triangles), "Three Little Pigs" (downward triangles); the Brick and clouds b−f (squares), Sgr B2 (diamonds), Sgr A* (circle with cross). All figures are adapted from Henshaw *et al.* 2016.

thus the relative distance of the clouds along the line-of-sight is difficult to determine. In addition, spectral line observations only yield the line-of-sight velocities of gas clouds but not the motion of the clouds in the plane of the sky. To fully understand the gas motions in the CMZ, we have to know its location in 6D space (position, distance, line-of-sight velocity, velocity in the plane of the sky). With this information, we will be able to test models interpreting the gas kinematics (see section 2).

The only method to develop a well-founded 6D picture of the CMZ is to measure parallaxes and proper motions of masers and to combine them with their positions and line-of-sight velocities. Methanol and water masers in star forming regions are particularly good targets since the motions of the host clouds can be easily inferred from the maser proper motions.

2. Orbital models

Recent models have tried to explain the inflow of gas towards and its kinematics in the CMZ. We will focus on the predictions of three models which interpret the kinematics within $|l| \leqslant 0.7°$: two spiral arms (e.g. Sawada *et al.* 2004, Ridley *et al.* 2017), a closed elliptical orbit (Molinari *et al.* 2011), continuous open streams (Kruijssen *et al.* 2015). Fig. 1 shows the projected and the top-down view of the predicted gas orbits of these three models, adapted from Henshaw *et al.* 2016. Important sources along the orbits are marked.

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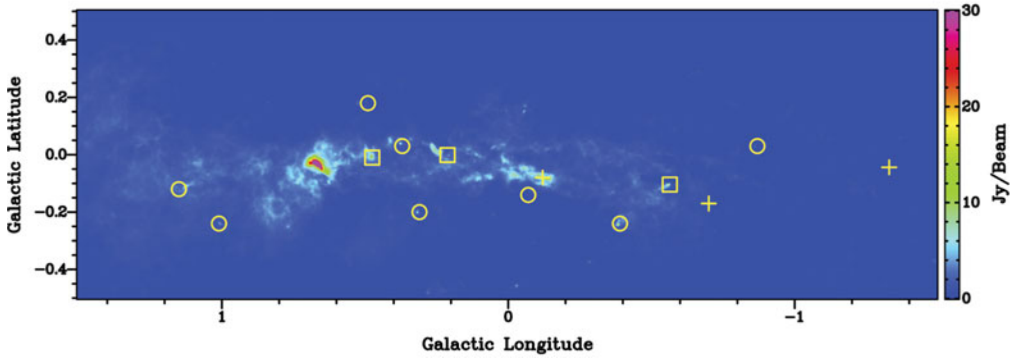

Figure 2. 870 μm emission of the CMZ from the ATLASGAL survey (Schuller *et al.* 2009). Maser sources from the BeSSeL survey are marked with yellow circles. Methanol and water masers from our target list are shown as yellow boxes and crosses, respectively.

At the position of Sgr C, the Molinari model predicts all motion to be along the line-of-sight, implying very small proper motions. The Kruijssen and the Sawada models predict significant proper motions but with opposite signs. For the 20 km/s cloud, the Sawada model predicts proper motion in the direction of decreasing Galactic longitudes, in contrast to the other two models. In all three models, most of the motion at this position should be in the plane of the sky and the proper motions should be large (5−10 mas/yr). At the position of cloud e, all models predict proper motions in the direction of increasing Galactic longitudes but with values differing by factors of several. The velocity structure at the south-west end of the Brick is complex. Proper motion measurements will show if the gas at this position is located at the near or far side of the orbit.

3. Observations

From the parallax observations of the BeSSeL survey (Brunthaler *et al.* 2011) we infer that methanol and water masers need to be stronger than 3 and 8 Jy, respectively, to be used as phase-referencing sources. We searched water and methanol maser catalogues, covering the CMZ, for masers stronger than these limits within $|l| \leqslant 1.5°$ and $|b| \leqslant 0.25°$. We selected three 6.7 GHz methanol and three 22 GHz water masers for parallax and proper motion observations with the Very Long Baseline Array (VLBA, project code: BI042). In addition, four methanol and five water masers from the BeSSeL survey were included in the project. The observations of project BI042 were conducted in 2016/2017. For both the methanol and water masers in BI042, four epochs were observed over the timespan of one year. The location of the masers in the CMZ are shown in Fig. 2.

4. Preliminary results

The analysis of the BI042 data is ongoing while it has recently been concluded for the BeSSeL sources. In the first epoch of BI042, all methanol masers have been detected while two of the water maser candidates do not show maser emission. The parallaxes and proper motion values of the BI042 masers will be determined within the next year.

Here, we will present the preliminary results of two water masers from the BeSSeL survey (G359.61−0.24 and G000.37+0.03, see Fig. 2 for their positions in the CMZ).

G359.61−0.24 To determine the parallax and proper motion of this source, we combined the data of three maser spots and two background quasars (J1748−2907 and

J1752−3001). The parallax is 0.370 ± 0.029 mas, which corresponds to a distance of $2.7^{+0.2}_{-0.2}$ kpc. Although the coordinates of this source position it within the CMZ area, its distance clearly locates it in the Scutum arm. This result shows the importance of combining the proper motion measurements of the CMZ sources with parallax measurements to exclude sources which are not physically part of the CMZ.

G000.37+0.03 For this maser, we combined the parallax measurements of two maser spots, using two different background quasars (J1745−2820 and J1748−2907). This resulted in a parallax of 0.125 ± 0.047 mas which corresponds to a distance of $8.0^{+4.8}_{-2.2}$ kpc. This distance locates the source within the CMZ, however, the uncertainty is very large. Additional epochs from future observations could reduce this uncertainty. The proper motion of this source is $\mu_x = -1.004 \pm 0.108$ mas yr^{-1} and $\mu_y = -2.474 \pm 0.288$ mas yr^{-1} which is consistent with the values that the Kruijssen model predicts at that position ($\mu_x = -0.76^{+0.36}_{-0.78}$ mas yr^{-1}, $\mu_y = -2.88^{+0.84}_{-0.78}$ mas yr^{-1}).

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