Astrophysical Masers:
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SWAG Water Masers in the Galactic Center

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Abstract. The Galactic Center contains large amounts of molecular and ionized gas as well as a plethora of energetic objects. Water masers are an extinction-insensitive probe for star formation and thus ideal for studies of star formation stages in this highly obscured region. With the Australia Telescope Compact Array, we observed 22 GHz water masers in the entire Central Molecular Zone with sub-parsec resolution as part of the large SWAG survey: "Survey of Water and Ammonia in the Galactic Center". We detect of order 600 22 GHz masers with isotropic luminosities down to $\sim 10^{-7}$ $L_\odot$. Masers with luminosities of $\gtrsim 10^{-6}$ $L_\odot$ are likely associated with young stellar objects. They appear to be close to molecular gas streamers and may be due to star formation events that are triggered at pericenter passages near Sgr A*. Weaker masers are more widely distributed and frequently show double line features, a tell-tale sign for an origin in evolved star envelopes.

Keywords. masers, Galaxy: center, radio lines: stars

1. Introduction

The Central Molecular Zone (CMZ; the inner ~ 500 pc) of the Milky Way is the nearest nucleus of any galaxy and allows us to study aspects of star formation processes under extreme conditions, such as high pressure gas, extreme tidal forces, strong radiation fields, and cloud-cloud shock zones. Gas flows from the Milky Way disk to the CMZ, where some of the gas appears to follow specific trajectories also known as orbits or streamers. Kinematic models of the streamers are given, e.g., in Molinari *et al.* (2011), Kruijssen, Dale, & Longmore (2015), or Ridley *et al.* (2017). Kruijssen, Dale, & Longmore (2015), in particular, predict that streamers near the pericenter to Sgr A* (which marks the center of the gravitational potential) may compress the gas and initiate a collapse and trigger star formation. Longmore *et al.* (2013) and Henshaw *et al.* (2016) show that indeed a star formation sequence can be observed in the CMZ, where a streamer after its Sgr A* pericenter passage contains dense gas with no obvious star formation (the "brick"), followed by consecutively more evolved star forming regions, culminating in Sgr B2, the most vigorous star formation site in the Milky Way. Downstream from Sgr B2, stellar clusters appear even more evolved, e.g. in the radio continuum-bright Sgr B1 region and further down in the Arches and Quintuplet stellar clusters. Krieger *et al.* (2017) and Ginsburg *et al.* (2016) also find evidence that gas near pericenter passages exhibit positive temperature gradients, which suggests that gas may indeed be compressed near those spots.

The CMZ is characterized by extreme optical extinction and radio lines are ideal to derive the evolutionary status of star forming regions along the possible star formation sequence. 22 GHz water ($6_{16} - 5_{23}$) masers are not affected by extinction and are produced in extreme environments, typically in shocked envelopes of evolved stars, outflows of young stellar objects (YSOs), or, in their most extreme form, in the accretion disks and jet-gas interfaces of active galactic nuclei (AGN). Maser luminosities from the different sources vary, where AGN related masers are extremely bright megamasers (e.g., Lo 2005; where the term 'megamasers' refers to a comparison with typical maser strengths of individual stellar sources in the Milky Way). Masers near evolved stars and YSOs are much less luminous and the most luminous source in the Milky Way reaches isotropic luminosities of $\sim 0.1\,L_\odot$ (W 49N, Liljestrom *et al.* 1989). Palagi *et al.* (1993) compare maser luminosities in the Milky Way and they find that water masers related to YSOs are on the high end of the luminosity function, whereas evolved stars only reach maximum luminosities of $\sim 10^{-4}\,L_\odot$. With luminosity cutoffs it is therefore possible to preferentially select YSOs and thus locate the related active zones of star formation.

2. SWAG: Survey of Water and Ammonia in the Galactic Center

The SWAG survey "Survey of Water and Ammonia in the Galactic Center" is ideally suited to obtain a rather comprehensive picture of the molecular gas toward the Galactic Center. This three year survey with the Australia Telescope Compact Array†, covers the entire CMZ in the 21.2-25.4 GHz frequency range with high spectral resolution of targeted 42 specific lines. This includes the 22 GHz water maser line, multiple transitions of the temperature tracer ammonia, photon-dominated and shock-dominated region tracers, and radio recombination lines. The resolution of SWAG is about $\sim 27''$ which corresponds to sub-pc resolution at the distance of the CMZ (8.5 kpc). First results of SWAG are described in Krieger *et al.* (2017), who analyze the temperature properties along the gas streamers based on multiple transitions of ammonia. Here we report on first results of the 22 GHz water maser ($6_{16} - 5_{23}$) transition.

3. Populations of Water Masers toward the CMZ

Maps of ammonia and water masers are shown in Fig. 1. The gas streamers mostly reside in the inner ~ 150 pc, the region that covers the area from Sgr B2 to Sgr C, roughly centered on the supermassive black hole Sgr A*. In Fig. 1, we plot the location and direction of the Kruijssen, Dale, & Longmore (2015) streamers on top of the gas distribution. Starting between Sgr C and Sgr A*, the streamer passes the first pericenter near Sgr A* and continues toward and beyond Sgr B2 (for a 3-dimensional picture, see Kruijssen, Dale, & Longmore 2015).

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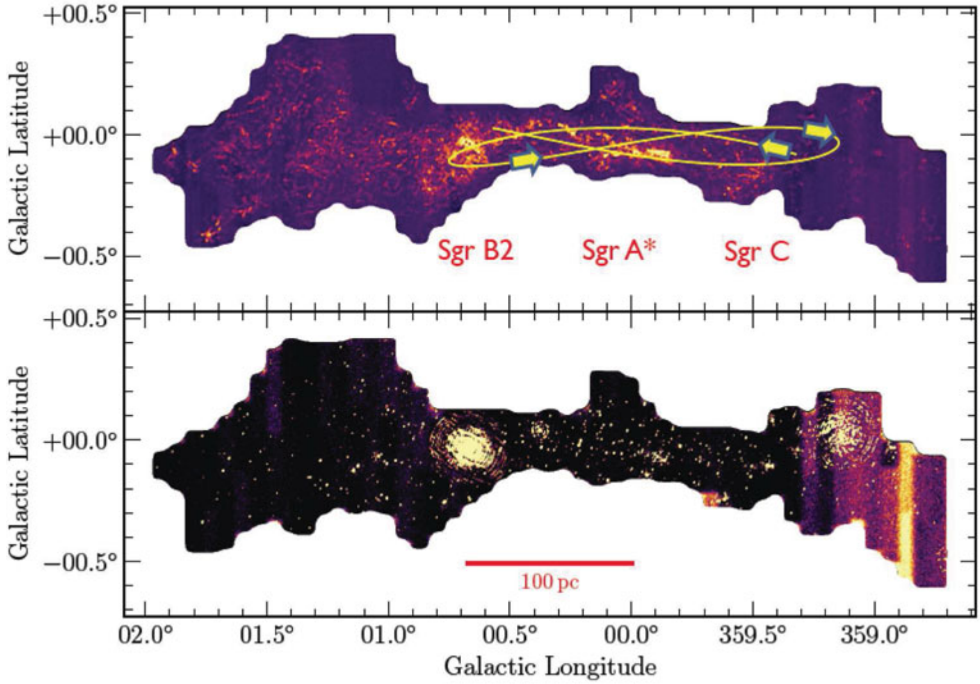

Figure 1. Top: Peak flux map of the ammonia (3,3) emission of the SWAG survey. Prominent features and the gas streamers are marked. The arrows indicate the direction of the flows. **Bottom:** The peak flux map of the 22 GHz water masers in the same region. Note that some extremely bright masers, in particular in the Sgr B2 region show considerable sidelobes.

The bottom of Fig. 1 shows the peak fluxes of the 22 GHz water masers. Note that some masers, especially near Sgr B2 and around $b \sim -0.8°$, are spilling beam sidelobes across many pointings. We consider those regions saturated and of limited use for the current analysis. To first order, the gas and the 22 GHz masers are not particularly correlated and a close inspection of the data shows that even on smaller scales masers and molecular clumps are not necessarily co-spatial.

In Fig. 2, we show masers in the inner region of the CMZ, spanning Sgr B2 to Sgr C, at different luminosity cuts (assuming that all water masers are at 8.5 kpc distance). The most luminous sources with isotropic luminosities exceeding $10^{-6}\,L_\odot$ are indeed close to the streamer trajectories. Following the work of Palagi *et al.* (1993), their luminosities are consistent with being related to YSOs and therefore trace current star formation sites. The gas and maser velocities are also frequently separated by less than $\sim \pm 20\,\mathrm{km\,s^{-1}}$, which further supports this scenario. Following the streamers, there is only one weak water maser source in the "brick" at $(l, b) \sim (0.253°, 0.016°)$ followed by a very bright $> 10^{-5}\,L_\odot$ source near $(l, b) \sim (0.38°, 0.04°)$; source "C", see Ginsburg *et al.* 2015) and the extreme Sgr B2 water masers. A few fainter masers but with luminosities still in the YSO regime are observed downstream. This situation corroborates the star formation sequence described by Longmore *et al.* (2013) and Henshaw *et al.* (2016).

At isotropic luminosities $\lesssim 10^{-6}\,L_\odot$, however, the number of sources increases drastically and in total we observe of order 600 masers. Their distribution does not follow streamers anymore but appear more widely distributed (see also Rickert 2017). Frequently, the masers show double-peaked spectral profiles, which suggests that the majority of them are associated with evolved stars across the entire disk of the Milky Way.

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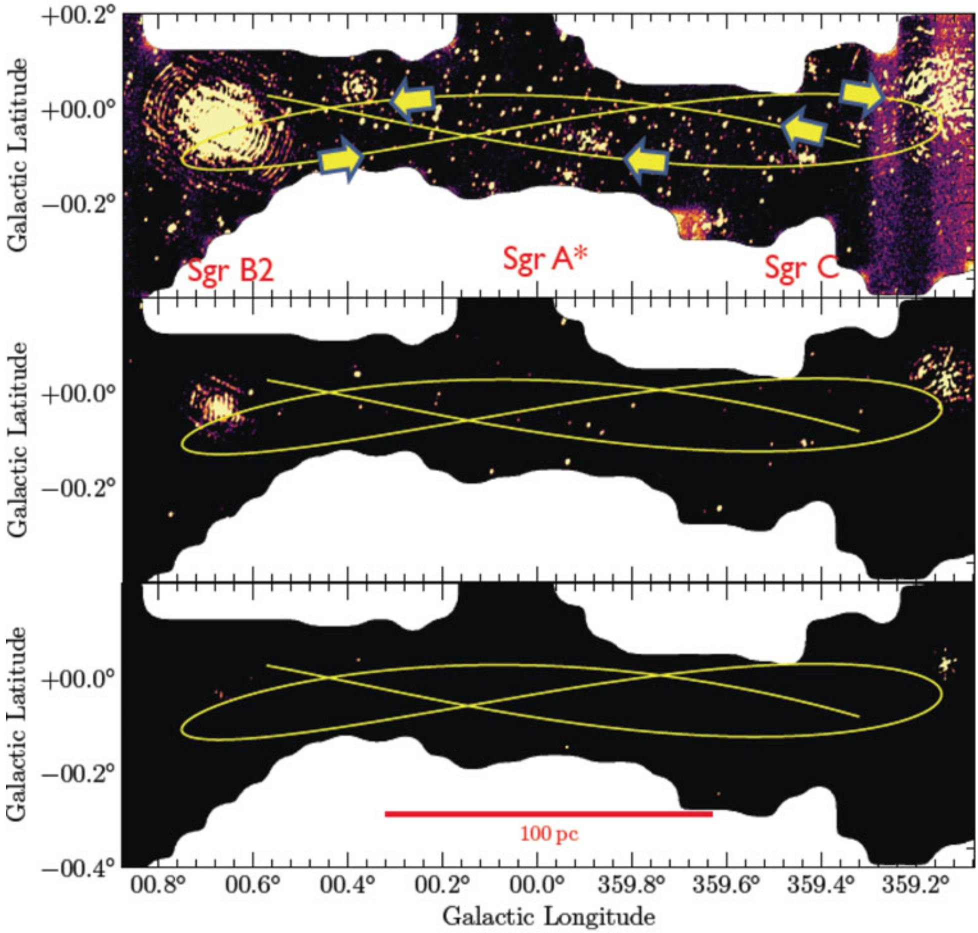

Figure 2. Water maser distribution at different isotropic luminosity cuts, assuming that all masers are at a distance of 8.5 kpc. **Top:** $> 10^{-7}\ L_\odot$ **Middle:** $> 10^{-6}\ L_\odot$ **Bottom:** $> 10^{-5}\ L_\odot$. Overlaid are the Streamers and directional arrows.

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