Cosmic Masers - from OH to H_0
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Class I Methanol Masers in the Galactic Center

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Abstract. We report on 36 and 44 GHz Class I methanol (CH_3OH) maser emission in the Sagittarius A (Sgr A) region with the Expanded Very Large Array (EVLA). At least three different maser transitions tracing shocked regions in the cm-wave radio regime can be found in Sgr A. 44 GHz masers correlate with the positions and velocities of 36 GHz CH_3OH masers, but the methanol masers correlate less with 1720 MHz OH masers. Our results agree with theoretical predictions that the densities and temperatures conducive for 1720 MHz OH masers may also produce 36 and 44 GHz CH_3OH maser emission. However, many 44 GHz masers do not overlap with 36 GHz methanol masers, suggesting that 44 GHz masers also arise in regions too hot and too dense for 36 GHz masers to form. This agrees with the non-detection of 1720 MHz OH masers in the same area, which are thought to be excited under cooler or denser conditions. We speculate that the geometry of the bright 36 GHz masers in Sgr A East outlines the location of a SNR shock front.

Keywords. Galaxy: center — Masers — Shock waves — Supernovae: individual(Sgr A East)

1. Introduction

The Sagittarius A complex is one of the best studied regions in the sky and encompasses several interesting phenomena like the nearest supermassive nuclear black hole (Sgr A*), the circumnuclear disk (CND), star forming regions (SFRs) and supernova remnants (SNRs). The line of sight toward the Sgr A complex consists of the SNR Sgr A East in the back and the CND (whose ionized part is known as Sgr A West) in the front partly overlapping with Sgr A East. Molecular gas is abundant and well distributed; the CND consists of irregularly distributed clumps of molecular gas and there are two giant molecular cloud cores (GMCs) called the +20 and +50 $\mathrm{km\,s^{-1}}$ clouds (M$-0.13-0.08$ and M$-0.02-0.07$ respectively). These GMCs form the molecular belt stretching across the Sgr A complex, providing the interstellar medium (ISM) that interacts with Sgr A East. A nice and recent comprehensive overview is presented by Amo-Baladrón, Martín-Pintado & Martín (2011).

Bright maser lines are useful probes of physical conditions within molecular clouds, especially when mapped in detail by interferometers. One example is the collisionally pumped 1720 MHz OH maser which is widely recognized as a tracer for shocked regions, observed both in SFRs and SNRs. In SNRs, Very Large Array (VLA) observations have shown that the OH masers originate in regions where the SNR shock collides with the interstellar medium (e.g. Claussen *et al.* 1997, Yusef-Zadeh *et al.* 2003, Frail & Mitchell 1998). Such OH masers are numerous in Sgr A East, thus probing the conditions of the interaction regions between the +50 and +20 $\mathrm{km\,s^{-1}}$ clouds and the SNR Sgr A East.

Dense gas structures in the Galactic center region, including Sgr A East, are traced by ammonia and methanol thermal emission (Coil & Ho 2000, Szczepanski *et al.* 1989,

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Szczepanski, Ho & Gusten 1991). Methanol abundances are high enough to produce maser emission. Like 1720 MHz OH masers, Class I methanol masers such as the 36 and 44 GHz transitions are excited through collisions. Theoretical modeling of collisional OH excitation predicts that the 1720 MHz OH should be found in regions of $n \geqslant 10^5$ cm^{-3}, $T \sim 75$ K (Gray, Doel & Field 1991, Gray, Field & Doel 1992, Wardle 1999, Lockett, Gauthier & Elitzur 1999, Pihlström *et al.* 2008). The number density and temperature required for 36 GHz methanol masers are near those modeled for 1720 MHz OH masers, with $n \sim 10^4 - 10^5$ cm^{-3} and $T < 100$ K (Morimoto, Kanzawa & Ohishi 1985, Cragg *et al.* 1992, Liechti & Wilson 1996). At least in SFRs, higher densities and temperatures, $n \sim 10^5 - 10^6$ cm^{-3} and $T = 80 - 200$ K, the Class I 44 GHz line will have optimized maser output, while the 36 GHz maser eventually becomes quenched (Pratap *et al.* 2008, Sobolev *et al.* 2005, Sobolev *et al.* 2007). These methanol masers may therefore constrain the density in the shocked SNR regions. In turn upper limits can be used to estimate the importance of compression by shocks in the formation of stars near SNRs.

That Class I methanol maser lines are detectable in SNR/cloud interaction regions was shown by Sjouwerman, Pihlström & Fish (2010), using the 7 first antennas outfitted with 36 GHz receivers at the Expanded VLA (EVLA). Several bright masers were found near the 1720 MHz OH masers in the Sgr A East molecular cloud - SNR interaction region; a feature also observed by many others (e.g. Tsuboi, Miyazaki & Okumura 2009). To see whether the relation between the collisionally excited 36 and 44 methanol masers and 1720 MHz OH holds in general, we here present the result of a search for Class I 44 GHz methanol maser emission in the Sgr A region.

Meanwhile we have surveyed the entire $\sim 6' \times 8'$ Sgr A complex for 36 and 44 GHz methanol emission for which the complete results will be reported elsewhere; here we concentrate on the early detections in the $\sim 4' \times 4'$ Sgr A region.

2. Observations and Results

The EVLA was used in its C configuration to observe the transition of CH_3OH at 44 069.41 MHz with a bandwidth of 8 MHz in dual polarization at a velocity resolution of approximately 0.2 km s^{-1}. The primary beam at 44 GHz is about 56″; initially we selected five pointing positions ("A" through "E", see Figure 1) with central velocities based on previous results on 1720 MHz OH masers and 36 GHz methanol masers. Later we covered the whole Sgr A region as part of a larger $\sim 6' \times 8'$ survey. Position A corresponds to a region of high-velocity 1720 MHz OH masers belonging to the circumnuclear disk, covering LSR velocities between 106 and 157 km s^{-1}. In position B we previously detected 36 GHz methanol masers at velocities around 23 km s^{-1} (LSR coverage −3 to +39 km s^{-1}). This pointing position partly overlaps on the sky with pointing position C which has a central velocity of 48 km s^{-1} (LSR coverage 22 – 74 km s^{-1}) based on the 1720 MHz OH masers. Finally, positions D and E correspond to a region where the 50 km s^{-1} molecular cloud interacts with Sgr A East, and where 1720 MHz masers are numerous. The LSR velocity coverage for these pointing positions was 22 – 74 km s^{-1}.

The data were reduced using standard procedures in AIPS, using 3C 286 as the flux density calibrator resulting in a typical absolute flux density uncertainty of 15%. In the fields were masers were found, a strong maser channel was used for self-calibration. Each cube was CLEANed with robust weighting down to a level of five times the theoretical rms over a field approximately twice the primary beam. This was necessary since some masers appeared in the sidelobes and needed to be accounted for in the CLEANing process. The resulting typical channel rms noise is 15 – 20 mJy/beam, and the restoring beam is 1.3×0.5″.

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The image cubes were searched for masers, and parameters for the individual features were extracted using the AIPS task JMFIT, with peak fluxes corrected for primary beam attenuation using PBCOR. A few weaker masers exist in the cubes, but they are all located close to the brighter masers in position and velocity, and will not change any of the discussion in Sect. 3.

A few features show more than one spectral peak at a given position, implying there is structure on scales smaller than the EVLA beam. Some spectral features have wings of weaker emission extending over $6-8$ km s^{-1}. Since the observations were taken when the EVLA was in C-configuration, we suspect that some of this broad and weak emission is of thermal origin. The peak flux density of the spectral features corresponds to brightness temperatures exceeding 10^3 K, but as both the 44 GHz and 36 GHz masers are thought to be excited by the same process, it is likely that at least the 44 GHz detections co-located with 36 GHz masers are masers too.

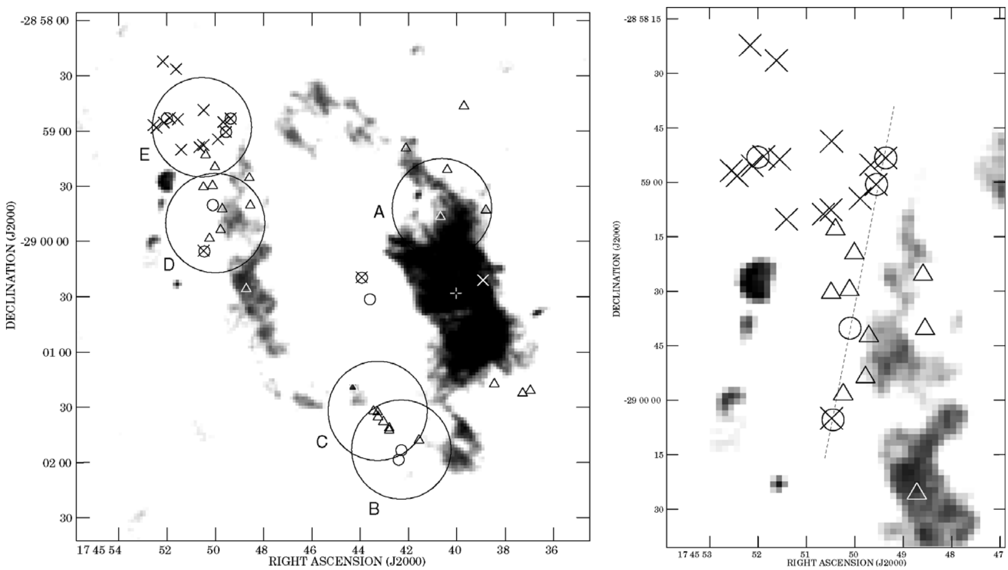

Figure 1. Relative sky positions of the 44 GHz methanol masers (crosses), 36 GHz methanol masers (circles) and 1720 MHz OH masers (triangles). The white plus symbol marks the position of Sgr A*. The large circles show the five field-of-view positions covered. A blow-up of the upper left region is shown at the right hand side, showing an apparent systematic offset in the location of the three maser species, with the 44 GHz methanol masers concentrated to the northeast (upper left), the 1720 MHz OH masers more to the southwest (lower right) and a NNW-SSE line of (four) very bright 36 GHz methanol masers, three co-spatial with 44 GHz, roughly dividing the two regions. The dashed line shows the alignment of 36 GHz masers with the shock front in the northnorthwest-southsoutheast direction.

Three masers were detected outside the primary beam (large circles in Figure 1) and their flux density is therefore less certain than for masers located within the primary beam. The position and velocity of maser 2 at 50 km s^{-1} agrees very well with the position of a 36 GHz maser at 51 km s^{-1} (Sjouwerman, Pihlström & Fish 2010), and we therefore trust that this detection is real. This 44 GHz maser has previously been reported on by Yusef-Zadeh *et al.* (2008), and is associated with a molecular clump 'G'. Similarly, we confirm their maser 'V' (our maser 1) in our data taken for the phase-reference calibrator J1745$-$2900 (i.e. Sgr A*), and both 'G' and 'V' in archival VLA data taken on 2009 April 23. The 44 GHz maser associated with clump 'F' reported by Yusef-Zadeh *et al.* (2008) is not confirmed by our, nor the archival, observations. The additional

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two masers detected outside the primary beam also do not have 36 GHz masers directly associated with them.

Figure 1 plots the position of the detected 44 GHz methanol sources compared to the previously detected 36 GHz and 1720 MHz OH masers. The right hand side panel of Figure 1 shows the northeast region of Sgr A East where most 44 GHz masers are located. From these plots a few main results can be concluded. Firstly, the positions and velocities of several 44 GHz masers (Figure 1) agree to within the errors with the values reported by Sjouwerman, Pihlström & Fish (2010) for the 36 GHz masers. Secondly, there is a systematic difference between the overall distributions of the 1720 MHz OH, 36 GHz methanol and 44 GHz methanol masers. In the northeast (upper left) region, in overlap with the densest part of the 50 $\mathrm{km\,s^{-1}}$ cloud, the 44 GHz masers are offset to the northeast with respect to a narrow, almost linear southsoutheast to northnorthwest distribution of the 36 GHz masers. The 1720 MHz OH masers are found on the other side of the 36 GHz masers, near the radio continuum of the SNR to the southwest (lower right). A positional offset between the OH and methanol is also observed in the southeastern interaction region, where the SNR G359.02–0.09 overlaps the Sgr A East continuum (Coil & Ho 2000, Herrnstein & Ho 2005). These positional offsets are discussed further in Sect. 3.

3. Discussion

3.1. *36 GHz versus 44 GHz Methanol Masers*

Modeling of methanol masers suggest that the 36 GHz transition occurs under somewhat cooler and less dense ($T \sim 30 - 100\,\mathrm{K}$, $n \sim 10^4 - 10^5\ \mathrm{cm}^{-3}$) conditions than the 44 GHz transition ($T \sim 80 - 200$ K, $n \sim 10^5 - 10^6\ \mathrm{cm}^{-3}$; see, e.g. Pratap *et al.* 2008). The range of physical conditions do however overlap, and some spatial overlap could therefore be expected. Seven 44 GHz masers show an almost perfect overlap in both position and velocity with 36 GHz masers (Sjouwerman, Pihlström & Fish 2010). Here, according to the modeling, the densities and temperatures should be close to $10^5\ \mathrm{cm}^{-3}$ and 100 K to produce both methanol maser lines.

It is striking that the brightest 36 GHz masers, all to the northwest in positions D and E (Sjouwerman, Pihlström & Fish 2010), are narrowly distributed along a line roughly from north to south, of which three coincide with 44 GHz masers in position and velocity within the errors. This NNW-SSE division more or less coincides with the sharp gradient in low-frequency radio continuum emission of the Sgr A East SNR (Pedlar *et al.* 1989) and appears to be located in the sheath in the CS emission as mapped by Tsuboi, Miyazaki & Okumura (2009). The mean velocity of each transition is 46 $\mathrm{km\,s^{-1}}$, implying that they arise in similar regions of the molecular cloud where the velocities still are less disturbed by the SNR shock (see Sect. 3.2). Apart from two individual exceptions located far from this area, we do not find any 44 GHz (nor 36 GHz) masers westward of this line in our pointings. It is therefore tempting to speculate that the line delineates the arrival of the shock front, where enough material has been swept up to provide the density for the creation of (perhaps due to geometry very bright 36 GHz) methanol masers, but not yet enough energy has dissipated to dissociate all methanol or to significantly disturb the velocity structure by means of a reverse shock (Section 3.2).

In the northeastern part of Sgr A East toward the core of the 50 $\mathrm{km\,s^{-1}}$ cloud, there is a group of 44 GHz masers with a distinct positional offset from the 36 GHz masers. The narrower distribution of 36 GHz masers suggests that the conditions required to produce masers in this transition are not fulfilled further to the northeast. The position of the 36 GHz emission is consistent with being just in the SNR/cloud interaction region, while

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the 44 GHz masers may be found deeper inside the denser parts of the cloud. These 44 GHz masers, which are typically found to be brighter than the 36 GHz masers, may originate near sites of massive star formation instead (e.g. Pratap *et al.* 2008, Fish *et al.* 2011). The lack of companion 36 GHz masers in this putative star-forming region (e.g. Tsuboi, Miyazaki & Okumura 2009) therefore may be due to the limited sensitivity of the 36 GHz observations. This picture, at least for this region in the Galactic center, in which 44 GHz masers are primarily associated with cloud cores and 36 GHz masers are found at the boundaries of the SNR interaction regions, is consistent with theoretical models indicating that 44 GHz masers can be produced at higher densities than 36 GHz masers. The existence of 36 GHz masers without accompanying 44 GHz masers in positions B and C may then indicate the interaction region of two SNRs without the presence of a dense cloud.

3.2. *OH versus Methanol Masers*

As is the case with Class I methanol masers, 1720 MHz OH masers are used as tracers of shocked regions. The presence of 1720 MHz OH masers indicates the presence of C-shocks (e.g. Lockett, Gauthier & Elitzur 1999). Modeling of OH and CH_3OH shows that the three maser transitions discussed here require similar densities and temperatures. This agrees well with the detection of all three masers in Sgr A East. However, we observe a distinct offset in positions between the methanol and OH masers (Figure 1). In the northeast interaction region between the 50 $\mathrm{km\,s^{-1}}$ cloud and Sgr A East the OH masers are found more to the southwest. In addition, the 1720 MHz OH masers have a higher mean velocity of $\sim$57 $\mathrm{km\,s^{-1}}$ versus $\sim$46 $\mathrm{km\,s^{-1}}$ for the methanol. However, the 1720 MHz OH does overlap in the sky with the line of 36 GHz masers.

A similar offset is observed in the southeastern interaction region in pointing positions B and C, where the methanol masers are offset southwest from the OH. The OH mean velocities here are 58 $\mathrm{km\,s^{-1}}$ to be compared to the 24.5 $\mathrm{km\,s^{-1}}$ for the 36 GHz methanol. No 44 GHz methanol was detected in this region.

The association between 1720 MHz OH and 36 GHz methanol emission may be due to the processes that form these molecules. OH is created by dissociation of H_2O (and maybe also CH_3OH), and the propagation of a C-shock creates densities and temperatures suitable for 1720 MHz OH inversion. Thus, OH masers should preferentially be found in the SNR post-shock region. This agrees with the OH masers being co-located with positions of radio continuum, outlining regions where electrons have been accelerated by the shock. The production of methanol is less well understood, but it is believed that methanol is released from grains, either by sputtering from a shock or by evaporation when temperatures reach above 100 K (Hidaka *et al.* 2004, Menten *et al.* 2009, Bachiller & Perez Gutierrez 1997, Voronkov *et al.* 2006, Hartquist *et al.* 1995).

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