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New masers and further developments in maser physics *Chair: Mark Reid*

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Cosmic Masers - from OH to H_0
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New class I methanol masers

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Abstract. We review properties of all known collisionally pumped (class I) methanol maser series based on observations with the Australia Telescope Compact Array (ATCA) and the Mopra radio telescope. Masers at 36, 84, 44 and 95 GHz are most widespread, while 9.9, 25, 23.4 and 104 GHz masers are much rarer, tracing the most energetic shocks. A survey of many southern masers at 36 and 44 GHz suggests that these two transitions are highly complementary. The 23.4 GHz maser is a new type of rare class I methanol maser, detected only in two high-mass star-forming regions, G357.97-0.16 and G343.12-0.06, and showing a behaviour similar to 9.9, 25 and 104 GHz masers. Interferometric positions suggest that shocks responsible for class I masers could arise from a range of phenomena, not merely an outflow scenario. For example, some masers might be caused by interaction of an expanding HII region with its surrounding molecular cloud. This has implications for evolutionary sequences incorporating class I methanol masers if they appear more than once during the evolution of the star-forming region. We also make predictions for candidate maser transitions in the ALMA frequency range.

Keywords. masers – ISM: molecules – ISM: jets and outflows

1. Introduction

Methanol masers are associated with regions of active star formation, with more than 20 different cm- and mm-wavelength masing transitions discovered to date. The whole range of methanol maser transitions does not share the same behaviour, being loosely grouped in two classes. The division stems from early empirical distinctions (e.g. Batrla *et al.* 1987). Class II methanol masers (e.g. the most famous 6.7-GHz transition), along with OH and H_2O masers, occur in the immediate environment of young stellar objects (YSOs) recognisable from their characteristic infrared emission. The class II methanol masers are exclusive tracers of high-mass star-formation (e.g. Minier *et al.* 2003; Green *et al.* 2012). In contrast, the class I masers (e.g. at 36 and 44 GHz), which are the subject of this paper, are usually found offset from the presumed origin of excitation (e.g. Kurtz *et al.* 2004; Voronkov *et al.* 2006), and are found in regions of both high- and low-mass star formation (Kalenskii *et al.* 2010 and their paper in this volume).

Theoretical calculations can explain this empirical classification, with the pumping process of class I masers dominated by collisions (with molecular hydrogen), in contrast to class II masers which are pumped by radiative excitation (e.g. Cragg *et al.* 1992; Voronkov 1999; Voronkov *et al.* 2005a). The two mechanisms are competitive (see Voronkov *et al.* 2005a for illustration): strong radiation from a nearby infrared source quenches class I masers and strengthens class II masers. The transitions of different classes occur in opposite directions between two given ladders of energy levels (Fig. 1). The equilibrium breaks first between the ladders giving rise to either class I or class II masers depending on whether radiational or collisional excitation dominates (e.g. Voronkov 1999). Therefore, bright masers of different classes residing in the same volume of gas are widely accepted as mutually exclusive (with potential exceptions for weak masers). However, on larger scales, they are often observed to coexist in the same star forming region within less than a parsec of each other (while a few archetypal sources exist, displaying only one class of methanol maser).

In addition to the gross classification, there are finer distinctions within the same class of methanol maser transitions. At sensitivity levels typically attained in surveys, the range of transitions can be further categorised into widespread masers (e.g. at 44 GHz) and rare or weak masers (e.g. at 9.9 GHz). Models seem to suggest that the formation of rare masers requires higher temperatures and densities (Sobolev *et al.* 2005). The maser transitions of methanol tend to form series (individual transitions have different J quantum numbers as is evident from Fig. 1). Observational properties such as whether the individual transitions give rare or widespread masers are qualitatively similar within the same series. Superposed are trends with J caused by the changes of excitation energy and the efficiency of the sink process due to a different number of energy levels below. Interestingly, all class II methanol maser series (with the exception of J_2-$(J\text{-}1)_3$ $A^{\pm}$ series based on the 38-GHz maser) are going downwards (with J decreasing while frequency increases) and eventually terminate. In contrast, all class I maser series extend upwards (see Fig. 1). Therefore, the majority of candidate maser transitions searchable with the Atacama Large Millimetre Array (ALMA) in the millimetre and sub-millimetre bands belong to class I. In the following sections we review observational properties of all known

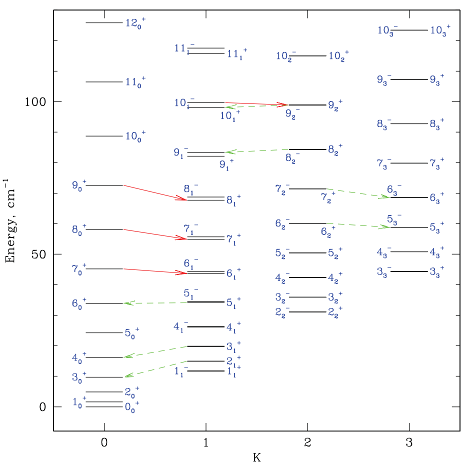

Figure 1. Energy level diagram for A-methanol (energies are given with respect to the lowest level of A-methanol). Solid (red) arrows represent known class I maser transitions, dashed (green) arrows show known class II masers.

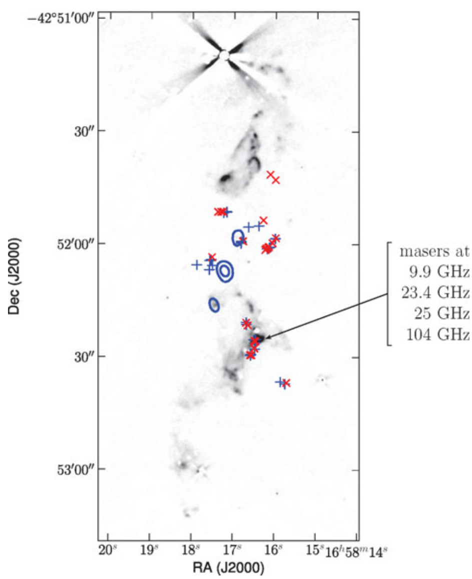

Figure 2. Distribution of the 36 (crosses) and 44 GHz (pluses) maser spots on top of the outflow image traced by 2.12μm H_2 emission in G343.12-0.06, contours show the 12mm continuum emission (see also Voronkov *et al.* 2006)

class I methanol maser series before summarising predictions for ALMA in bands 6 and 7. For simplicity, we refer to the maser series by the lowest frequency transition.

2. Widespread class I masers (series based on 36 and 44 GHz masers)

The J_0-$(J\text{-}1)_1$ A^+ methanol series includes the most studied 44 and 95-GHz class I methanol masers. A few hundred such masers are currently known, but the majority have only single dish data (e.g. Haschick *et al.* 1990; Slysh *et al.* 1994; Val'tts *et al.* 2000; Ellingsen 2005; Fontani *et al.* 2010; Chen *et al.* 2011; unpublished Mopra data from our group). The major published interferometric surveys are those of Kurtz *et al.* (2004) and Cyganowski *et al.* (2009). The second class I maser series in the widespread category is J_{-1}-$(J\text{-}1)_0$ E which is renowned for masers at 36 and 84 GHz. These two maser transitions are considerably less studied than the 44 and 95-GHz pair. As before, most observational data are obtained with single dish facilities (e.g. Haschick & Baan 1989; Kalenskii *et al.* 2001). The reported interferometric observations are scarce and confined to single source papers only (e.g. Voronkov *et al.* 2006; Voronkov *et al.* 2010; Sjouwerman *et al.* 2010; Fish *et al.* 2011). The typical spread of maser spots is comparable to or exceeds the beam size of a 20-m class single dish at the frequencies of these transitions (Kurtz *et al.* 2004; Voronkov *et al.* 2006). Therefore, interferometric observations, which allow us to measure positions of each maser sport accurately, are crucial even to get meaningful detection statistics.

To increase the number of class I masers studied at high angular resolution and to compare the morphologies observed in different maser transitions we carried out in 2007 a quasi-simultaneous interferometric survey at 36 and 44 GHz of all class I masers reported in the literature at the time of the observations and located south of declination -35^o (a single source from the project was presented in Voronkov *et al.* 2010a). Fig. 2 shows the results of this survey for G343.12-0.06, which has been studied in detail in other transitions by Voronkov *et al.* (2006). The distribution of 36 and 44 GHz maser spots resembles that of 84- and 95-GHz maser spots from Voronkov *et al.* (2006), which is a good example of outflow association, but also has a few new spots found due to the larger primary beam and higher signal-to-noise ratio of the new observations. Note, that all rare masers in this source are located at the same position near the brightest knot of the 2.12 μm molecular hydrogen emission, which is a well known shock tracer (Voronkov *et al.* 2006). With the caveat about extinction variations, this supports the idea that the formation of rare class I masers requires higher temperatures and densities than the widespread masers (Sobolev *et al.* 2005).

In G343.12-0.06, the majority of 44-GHz maser spots have some 36-GHz emission and vice versa (Fig. 2). However, in many cases these two transitions were found to be highly complementary. Fig. 3 shows the maser spot distribution in G333.466-0.164, the best example of such a scenario that we currently have. The 44-GHz maser spots are distributed roughly along the line traced by the source of extended infrared emission with 4.5-μm excess (often referred to as an Extended Green Object or EGO). Without the 36-GHz data, this EGO would most likely be interpreted as tracing an outflow emanating from the location of the YSO marked by the 6.7-GHz maser (shown by square in Fig. 3). The chain of 36-GHz maser spots completes the second half of a bow-shock structure suggesting a different direction of the outflow. Another good example is the high-velocity feature blue-shifted by about 30 km s^{-1} from the systemic velocity which was found in G309.38−0.13 at 36-GHz only (Voronkov *et al.* 2010a). It is worth noting, that Sobolev *et al.* (2005) suggested that the 36 to 44-GHz flux density ratio is very sensitive to the orientation of the maser region.

3. Rare 9.9 and 104 GHz masers

These masers belong to the J_{-1}-$(J\text{-}1)_{-2}$ E methanol series, J=9 and 11, respectively. The first search for 9.9-GHz masers was carried out by Slysh *et al.* (1993) who reported a single maser detection towards W33-Met (G12.80−0.19). Recently, Voronkov *et al.* (2010b) carried out a sensitive (1σ limits as low as 100 mJy) survey at 9.9-GHz with the ATCA and found 2 new detections out of 46 targets observed. Two additional 9.9-GHz masers in G343.12−0.06 and G357.97−0.16 were found serendipitously (Voronkov *et al.* 2006, 2011). The latter maser is the strongest, with peak flux density around 70 Jy and the only one for which the absolute position has not been measured (although the position is expected to be the same as for the 23.4-GHz maser found in this source).

With the exception of the 104-GHz maser in G343.12−0.06 which had ATCA observations (Voronkov *et al.* 2006), all other currently known 104-GHz masers were found using single dish facilities (Voronkov *et al.* 2005b, 2007). In addition to the sources of 9.9-GHz maser emission described above, these observations brought only one new maser in G305.21+0.21. It is worth noting that a weak maser at 9.9 GHz was seen towards this source during test ATCA observations, but happened to be below the detection threshold of the regular survey (Voronkov *et al.* 2010b). This brings the total number of known masers in this series to 6, in contrast to more than 200 hundred known widespread masers.

Detailed investigations of these masers suggest that some class I masers (in all classes of transitions, not just 9.9-GHz) may be caused by expanding HII regions (see e.g. Fig. 4 and Voronkov *et al.* 2010b). This is an additional scenario to the commonly accepted mechanism for the formation of class I masers in the outflow shocks.

4. Evolutionary stage of star-formation with class I masers

The question whether different masers trace distinct evolutionary stages of high-mass star formation has recently become a hot topic (see e.g. Breen *et al.* 2010 and references therein), although the place of class I masers in this picture is still poorly understood. Ellingsen (2006) investigated the infrared colours of GLIMPSE (Galactic Legacy Infrared

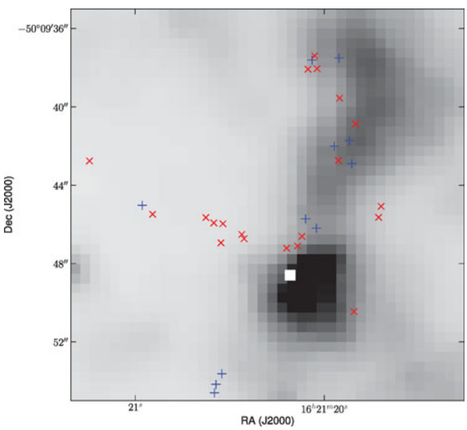

Figure 3. Distribution of the 36 (crosses) and 44 GHz (pluses) maser spots in G333.466-0.164. The position of the 6.7-GHz maser is shown by filled square. The background is GLIMPSE 4.5-μm image.

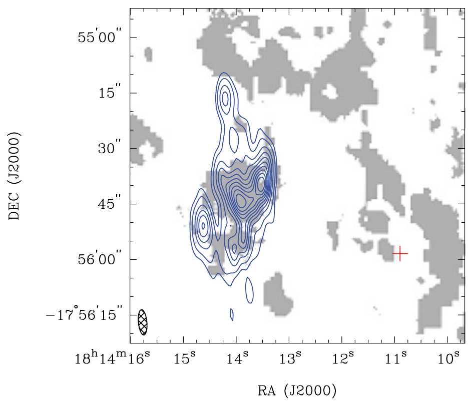

Figure 4. The position of the 9.9-GHz methanol maser in W33-Met. The contours represent 8.4-GHz continuum image, grayscale shows the distribution of the thermal NH_3 emission (for details see Voronkov *et al.* 2010b and references therein).

Mid-Plane Survey Extraordinaire) catalogue point sources associated with methanol masers and suggested that class I methanol masers may signpost an earlier stage of high-mass star formation than the class II masers. These and other considerations laid the foundation for a qualitative evolutionary scheme for different maser species proposed by Ellingsen *et al.* (2007). The scheme was further refined by Breen *et al.* (2010) in their Figure 6, but with no new survey data available on class I masers the conclusion about the evolutionary stage when these masers are present remained essentially the same. Voronkov *et al.* (2006, 2010b) pointed out that this statement is inconsistent with detailed studies of class I maser sources which do overlap with OH masers. Moreover, we carried out a search for the 44-GHz class I methanol masers towards known OH masers which were not detected at 6.7-GHz (class II) in the unbiased Methanol Multi-Beam (MMB) survey (Green *et al.* 2012 and references therein). Despite the inadequate spectral resolution (about 7 km s^{-1}) achieved in these test observations, which makes the survey insensitive to weak (<15 Jy) masers, the detection rate exceeded 50%. Therefore, it seems more appropriate to place the class I methanol masers as partly overlapping, but largely post-dating the evolutionary phase associated with class II methanol masers. The suggested association with expanding HII regions also implies that some of the sources are quite evolved. Whether there is a population of class I masers pre-dating the phase with the class II masers is unclear at present (see Voronkov *et al.* 2010b and Chen *et al.* 2011 for detailed discussion of these issues).

It is also important to keep in mind the major assumptions which underlie the evolutionary timeline suggested by Ellingsen *et al.* (2007) and Breen *et al.* (2010). In particular, that each major maser species arises only once during the evolution of a particular star formation region, and that all the maser species are associated with a single astrophysical object. The large spatial (and angular) spread of class I maser spots makes such identifications much less clear given a generally crowded environment of high-mass star formation where sequential or triggered star formation may take place. It is possible that one YSO in the cluster may have an associated 6.7-GHz maser, while another could be associated with OH masers and a well developed HII region. At this stage the number of sufficiently simple sources studied in detail is quite limited, hindering the statistical analysis and even in relatively simple sources some controversy may exist (see e.g. the case of G357.97−0.16 discussed by Britton *et al.*, this volume). It is worth noting that the survey of Chen *et al.* (2011) supports the hypothesis that class I masers may arise at more than one evolutionary phase.

5. Weak 25-GHz series

Historically, the first methanol masers found in space were from the J_2-J_1 E class I methanol maser series near 25-GHz towards Orion (Barrett *et al.* 1971). Very few additional sources were found in the following 3 decades, so these masers were widely believed to be rare. Voronkov *et al.* (2007) searched for J=5 transition of this maser series towards 102 targets with ATCA (although no absolute position was measured during this experiment). This search yielded 66 detections, but mostly weaker than 1 Jy. Other recent studies (e.g. Brogan *et al.* 2011; paper in this volume) also suggest that these masers are common, but typically weak. The new ATCA backend enabled simultaneous observations of up to 9 (limited by the receiver frequency range) transitions of this series (e.g. Wilson *et al.* (2011). Britton & Voronkov (paper in this volume) have recently followed up the majority of known southern 25-GHz masers in the J=2 to J=9 transitions.

6. New rare class I methanol maser at 23.4-GHz

The H_2O southern Galactic Plane Survey (HOPS; Walsh *et al.*, 2011 and their paper in this volume) brought an unexpected discovery of a new class I methanol maser at 23.4-GHz in G357.97−0.16 (see Voronkov *et al.* 2011 for details). This is the first transition in the J_1-$(J\text{-}1)_2$ A^- class I maser series (corresponding to J=10). A weaker 23.4-GHz maser was found in G343.12−0.06. Observational properties of this new maser are similar to other rare masers like that at 9.9-GHz. The source of strongest 23.4 and 9.9-GHz maser emission, G357.97−0.16, is discussed in detail by Britton *et al.* (this volume).

7. Class I methanol masers at high spatial resolution

In contrast to class II methanol masers, Very Long Baseline Interferometry (VLBI) observations of class I masers were effectively abandoned following a few unsuccessful attempts in early 1990s (which remained unpublished). The understanding of class I masers has certainly progressed since then and observations with connected element interferometers have become available (e.g. Kurtz *et al.* 2004; Cyganowski *et al.* 2009; see also earlier sections). In hindsight, the reasons for failure to detect class I masers in early VLBI experiments were not limited to larger intrinsic sizes of maser spots and a general difficulty doing high-frequency VLBI. First, only single dish positions (accurate up to arcmin) were available for most if not all of the targets. It is shown in the previous sections that images of class I masers typically contain several spots distributed over a large area often covering the whole primary beam of the telescope (see also Voronkov *et al.* 2006; Kurtz *et al.* 2004). Therefore, there are high chances to miss a spot of emission given a typical narrow field of view achieved in a VLBI experiment. In addition, the lack of images at arcsecond resolution made the selection of best most compact targets difficult. Recent VLBI observations (Tarchi, priv. comm.) at 44-GHz revealed fringes at the shortest baselines (similar observations were also carried out by Kim *et al.* (priv. comm.) with the Korean VLBI Network). The second issue is the selection of maser transition. The early VLBI attempts targeted the strongest and most widespread maser transitions at 44 and 95-GHz transitions. However, these are likely to have larger intrinsic source sizes being easier to excite than, for example, masers at 9.9 and 23.4 GHz along with the masers in the series near 25 GHz. It is worth noting that VLBI observations of 10 strongest 25-GHz masers have recently been carried out with the Long Baseline Array (LBA).

8. Millimetre and sub-millimetre masers with ALMA

One can extend the maser series reviewed in the previous sections to higher frequencies. ALMA bands 6 and 7 (already implemented) encompass the following candidate maser transitions. The series based on the 36-GHz maser giving 8_{-1}-7_0 E at 229 GHz (a known maser: Slysh *et al.* 2002; Fish *et al.* 2011), 9_{-1}-8_0 E at 278 GHz recently found in S255N with the SMA (Salii, Sobolev, Zinchenko, Liu & Su, priv. comm) and 10_{-1}-9_0 E at 327 GHz, although the system performance is poor for the latter transition. The series based on the 44-GHz maser giving 11_0-10_1 A^+ at 250 GHz, 12_0-11_1 A^+ at 303 GHz and 13_0-12_1 A^+ at 356 GHz. The series based on the 9.9-GHz maser giving 14_{-1}-13_{-2} E at 242 GHz, 15_{-1}-14_{-2} E at 287 GHz, 16_{-1}-15_{-2} E at 331 GHz. The new series based on the 23.4-GHz maser giving 14_1-13_2 A^- at 237 GHz, 15_1-14_2 A^- at 291 GHz and 16_1-15_2 A^- at 346 GHz.

The field of high-frequency class I methanol masers is essentially uncharted territory. For possible masers at even higher frequencies (e.g. ALMA band 9), it is hard to make sensible predictions. The transitions listed above correspond to excitation energies of about 300-500 K. The 25-GHz transitions are a cm-wavelength series but, between the same two ladders of levels, is the J_2-$(J\text{-}1)_1$ E series which gives mm-wavelength transitions including a 218-GHz maser (J=4) detected in the SMA observations mentioned above. It is worth noting that maser models predict population inversion for all these transitions (see also Sobolev *et al.*, this volume).

9. Conclusions

(*a*) Studies of different maser transitions are very complementary (filling the dots in morphology, high-velocity features and modelling).

(*b*) Rare/weak class I methanol masers (9.9, 23.4, 25 and 104 GHz) trace stronger shocks and higher temperatures and densities.

(*c*) Some class I masers may be caused by expanding HII regions, a scenario additional to their formation in outflows. An implication for a maser-based evolutionary sequence is that class I methanol masers may appear more than once during YSO evolution, and thus some regions with class I masers are probably quite evolved.

(*d*) The evolutionary stage with class I masers probably outlasts the stage when the 6.7-GHz methanol masers (class II) are present, overlapping with OH maser activity.

(*e*) Promising ALMA maser targets are G343.12-0.06 and G357.97-0.16.

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