Cosmic Masers - from OH to H_0
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Masers in star forming regions

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Abstract. Maser emission plays an important role as a tool in star formation studies. It is widely used for deriving kinematics, as well as the physical conditions of different structures, hidden in the dense environment very close to the young stars, for example associated with the onset of jets and outflows. We will summarize here the recent observational and theoretical progress on this topic since the last maser symposium: the IAU Symposium 242 in Alice Springs.

Keywords. masers – stars: formation – stars: early-type – radio lines: ISM – ISM: molecules – ISM: jets and outflows – ISM: kinematics and dynamic

1. Introduction

Cosmic masers are known as a unique tool in star-formation studies and are one of the first observed signposts of high-mass star formation, particularly the hydroxyl (OH), water (H_2O) and methanol (CH_3OH) masers, that are common and intense. This is demonstrated by the many results presented in this volume.

At the last IAU Symposium 242 in Alice Springs, Fish (2007) summarized the relation between masers and star-formation in the following way *"maser observations are at the vanguard of star formation research: yesterdays observations can be explained by complementary data and theory today, and todays observations lay the groundwork for the breakthroughs that will be achieved in the context of tomorrow."* In this review we will summarize some of the achievements and discoveries in the area of star-formation masers presented in the literature since the Australian Symposium. It is important to evaluate what "yesterday's tomorrow" has unveiled in the area of star formation and identify the possible "today's tomorrow" breakthroughs.

2. Population studies

It was relatively well established from earlier surveys of masers in our Galaxy that massive star-forming regions can be associated with OH, H_2O and Class II CH_3OH masers (e.g., Caswell et al. 1995, Szymczak et al. 2002). However, there is still a great need for verifying what the relation is between specific stages and classes of star formation and different masers. For this, complete and ever more sensitive surveys with better astrometric precision are most valuable. For example, since our previous meeting Green et al. (2009) discovered that high-mass star formation (HMSF) is present in both the far and near 3 kpc arms through 49 detections of 6.7 GHz methanol masers. The Red MSX Sources (RMS) based survey by Urquhart et al. (2009) investigated the statistical correlation of water masers with early-stages of massive star-formation. They found similar detection rates for UC H II regions and MYSOs, suggesting that the conditions needed for maser activity are equally likely in these two stages of star formation.

Nowadays, more instruments have become available, especially to focus systematically on different maser transitions like the higher excited methanol masers from both Class I (collisional excitation) and II (radiative excitation) methanol, as well as silicon monoxide (SiO), ammonia (NH_3) and formaldehyde (H_2CO) masers. Details are presented by e.g. Kurtz, Kalenskii, Voronkov, Sjouwerman, Wootten, Booth, Kim, Pestalozzi, Brogan and their collaborators in these proceedings.

In addition, yesterday's key-questions, which were deemed essential in order to use masers for studying the physics of star formation, are still not fully answered:

- Is there an evolutionary sequence based on maser occurrence?
- Are Class I and Class II methanol masers associated?
- Where, when and how exactly do masers arise?
- What physical conditions are needed to produce the maser(s)?

These questions require systematic studies of a large number of sources, possibly at high angular resolution, as well as observations of specific sources using multi-wavelength observations, in order to converge and refine our hypotheses. For example, single-dish studies suggested at first that the methanol Class I and II are coincident, but later interferometric images showed they are not co-spatial on arcsecond scales, even though they may be driven by the same YSO (Cyganowski et al. 2009).

2.1. *Methanol masers, the most widespread masers in HMSFRs*

Methanol masers have been widely studied, particularly after the discovery of the widespread, bright 6.7 GHz transition (Menten 1991). Many transitions have been found to emit maser emission from both the A and E types and they have been classified into Class I and Class II, which are collisionally and radiatively excited, respectively (Cragg et al. 1992). In general, the Class I (e.g., 36 and 44 GHz lines) are likely associated with outflows (lying further from the central objects) while the Class II (e.g., 6.7 and 12.2 GHz transitions) often coincide with hot molecular cores, UC H II regions, OH masers and near-IR sources.

The most common Class II masers are 6.7 and 12.2 GHz lines that according to the models (e.g., Cragg et al. 2005) should co-propagate quite often, as confirmed by observations (e.g., Breen et al. 2011). Both masers are strongly associated with HMSFRs and enable us to probe the dense environments where stars are being born. A large sample of 113 sources with known 6.7 GHz masers and 1.2-mm dust clumps was searched at 12.2 GHz by Breen et al. (2010b). These authors found out that when the 6.7 GHz emission is more luminous, then the evolutionary stage of the central object tends to be more advanced, while also the 12.2 GHz is often associated with more evolved regions. Based on this an evolutionary sequence for masers associated with massive star formation regions was proposed, which is consistent with conclusions of e.g. the survey of Class I by Pratap et al. (2008). However, some discussion continues to refine this relation, e.g. Fontani et al. (2010) and Chen et al. (2011).

2.1.1. *Class I and Class II methanol masers*

One of the key research areas over the past few years has been on relatively rare methanol masers. Voronkov et al. (2010b) found two new detections of 9.9 GHz Class I masers. To date we know of 5 masers at 9.9 GHz (additionally from Slysh et al. 1993, Voronkov et al. 2006, 2011). The detection rate is likely so low because of the strong dependence of the maser brightness on the physical conditions (Sobolev et al. 2005). This maser is believed to trace shocks caused by different phenomena (e.g., expanding

H II regions, outflows). A particularly interesting case is G331.13−00.24, which shows periodic variability at 6.7 GHz with a period of 500 days (Goedhart et al. 2004). There is an obvious urgency to verify whether the variations of both lines correlate, pointing to a common origin of the seed radiation and providing an estimate of the physical conditions for that. For more details see Voronkov et al. (these proceedings).

There are now also first arcsecond-resolution images of the 36 GHz methanol masers in HMSFRs thanks to the upgrades of both ATCA and EVLA, e.g. in M8E (Sarma & Momjian 2009), Sgr A (Sjouwerman et al. 2010b), G309.38−0.13 (Voronkov et al. 2010a) and DR21 (Fish et al. 2011b). In the latter case it was found that surprisingly the Class I 36 GHz and 229 GHz masers appear in close proximity (also in velocity) with the Class II 6.7 GHz maser, while the 44 GHz Class I masers is absent. According to the model by Voronkov et al. (2005) such cases require an intermixed environment of dust and gas at a lowish temperature of ≈60 K.

One may wonder whether we have come closer to answering the question *"when do Class I masers appear?"*. Chen et al. (2011) searched 192 EGOs (the candidates associated with ongoing outflows) for 95 GHz methanol masers, resulting in a 55 per cent detection rate. These detections are likely associated with the redder GLIMPSE point-source colors. There are two possible explanations, either the Class I objects are associated with lower stellar masses or they are associated with more than one evolutionary phase during high-mass star formation, apparently contradicting the most straightforward schemes (e.g. Breen et al., 2010b). Marseille et al. (2010) compared the physical conditions by observing several molecular tracers in both weak and bright mid-IR emitting massive dense cores. The methanol Class I maser at 84.5 GHz was found to be strongly anti-correlated with the 12 μm source brightness, leading to an interpretation that these represent more embedded mid-IR sources with a spherically symmetric distribution of the envelope material.

Ellingsen et al. (2011) searched for rare and weak methanol masers at 37.7, 38.3, 38.5 GHz Class II methanol masers towards 70 HMSFRs. They detected 13 at 37.7 GHz and 3 at 38.3/5 GHz and found that the 37.7 GHz masers are associated with the most luminous 6.7 and 12.2 GHz masers, likely representing a short (of 1000–4000 years) period in an advanced stage of the evolution. Therefore, the 37.7 GHz methanol masers may be called the *horsemen of the apocalypse* for the Class II methanol maser phase.

2.1.2. *The morphology of 6.7 GHz masers*

More sensitive VLBI surveys have led to the discovery of more complex 6.7 GHz maser structures, including several that show a ring-like morphology (Bartkiewicz et al. 2005, 2009). Kinematics of the maser spots revealed that outflow/infall dominates over the possible Keplerian rotation in a disc. A similar morphology with a similar kinematic signature was found in the well-known HMSFR Cep A, where, due to additional constraints on the orientation, the radial motions are more likely resulting from infall (Torstensson et al. 2011a, Sugiyama et al. 2008). Moreover, it seems that the magnetic field plays a role in shaping this morphology (Vlemmings et al. 2010). Such ring-like characteristics were also seen in water masers associated with slightly more advanced stages, where masers were likely tracing an accretion disc or its remnant (Motogi et al. 2011a). Torstensson et al. (2011b) analysed some of these ring-like maser sources using thermal emission at arcsec scale and found that mostly the distribution of the methanol gas peaks at the maser position with the larger scale gas showing a modest outflow velocity. They argued that the methanol gas has a single origin in these sources, possibly associated with an accretion shock. ALMA resolution is necessary for probing the regions of interest at size scales of 1000 AU.

For all of these studies it is important to remember that the VLBI technique resolves out some of the emission. Pandian et al. (2011) noted that more complex morphologies and often larger structures become apparent when using shorter baseline interferometers (EVLA, MERLIN) compared to VLBI, analyzing a study of 72 sources from the Arecibo Methanol Masers Galactic Survey. Thus, the 29% detection of the methanol rings of Bartkiewicz et al. (2009) may be biased by observational effects. Similarly, Cyganowski et al. (2009) also noted that shorter baselines observations resulted in more complex and extended emission for two targets from the EVN sample of Bartkiewicz et al. (2009). On the other hand, comparing Pandian et al. (2011) and Bartkiewicz et al. (2009) results, we note that in three out five cases the emission is very similar on EVN and MERLIN images, but this does not include any of the ring sources.

3. Gas kinematics through proper motion studies of masers

There has also been significant progress on maser proper motion studies at the milli-arcsecond scale. These result from multi-epoch observations that often have two simultaneous objectives: proper motions of the maser features in order to derive the kinematics of the gas in the direct environment of the YSOs and accurate direct distances by means of detecting the parallax. The parallax measurements are summarized and presented in this volume by e.g., Reid, Honma et al., Nagayama et al., Choi et al. (these proceedings).

Here we focus on the dynamical studies. In a series of papers, Moscadelli et al. (e.g., 2007, 2011a) demonstrated the power of multi-epoch VLBI for tracing the 3D kinematics close to an YSO towards nine well-studied HMSFRs. Combining observations of 22 GHz water and 6.7 GHz methanol masers within a time-span of a few years they detected various motions such as outflow, rotation, infall, all happening in the direct environments of these YSOs. They pointed out that these velocity gradients on milli-arcsecond scales still reflect large-scale (100-1000 AU) motions (Moscadelli et al. 2011b). In some cases such studies can constrain the YSO position and mass. For example, Goddi et al. (2011) directly measured these different phenomena going on within 400 AU from the high-mass protostar AFGL 5142; the gas infall is traced by the 3D velocities of the methanol masers, while a slow, massive, collimated, bipolar outflow is detectable through the water masers. Very detailed dynamics were registered by Torrelles et al. (2011) who used multi-epoch data of water masers towards Cep A HW2, noticing morphological changes at scales of 70 AU in a time-span of 5 years. They also argued that the R5 expanding bubble structure has been dissipating in the circumstellar medium and that a slow, wide-angle outflow at the scale of 1000 AU co-exists with the well-known high-velocity jets.

In addition to these methanol and water maser observations, there are unique data from SiO masers, although they are quite rare around YSOs. Matthews et al. (2010) observed the Orion Source I at both 43.1 and 42.8 GHz transitions, resulting in a most detailed view of the inner 20-100 AU of a MYSO. The SiO masers lie in an X-shaped structure, with clearly separated blue- and redshifted emission, while bridges of intermediate-velocity emission connect both sides. They proposed that these masers are related to a wide-angle bipolar wind emanating from a rotating, edge-on disc. This provides direct evidence of the formation of a MYSO via disc-mediated accretion. Other examples and more explanations can be found in contributions by e.g. Sanna et al., Goddi et al., Sawada-Satoh et al., Sugiyama et al. (these proceedings).

4. Physical conditions for maser emission

In order to answer the key question *where, when and how exactly do masers arise?*, we must probe the physical conditions in which they form. Such studies concern multiple maser transitions and studying the masing regions at a wide range of wavelengths. Both surveys of a large number of sources, as well as detailed individual source observations are needed to complete the scenario of maser formation. A very good example is the result obtained by Cyganowski et al. (2008) that Class I and II methanol masers coincide with so-called extended green objects (EGOs) which are indicators of outflows and are a promising starting point for identifying MYSOs (Cyganowski, these proceedings).

Breen et al. (2010a) investigated the OH/H_2O/CH_3OH relation for a large sample of HMSFRs and noticed a closer similarity of the velocities of OH and methanol masers than of either of these species compared to the water maser peak velocity. In spite of the different pumping schemes of water and methanol masers, they both show a similar, 80% detection rate association with OH sources. It also has been found by comparing high-luminosity masers with low-luminosity ones that the high brightness ones are related to lower NH3(1,1) excitation temperatures, smaller densities, but three times larger column densities. Moreover, the high-luminosity sources are associated with 10 times more massive molecular cores, larger outflows and their internal motions are more pronounced (Wu et al. 2010). Interestingly, Pandian et al. (2010) showed that the continuum of the counterparts of 6.7 GHz methanol masers is consistent with rapidly accreting massive YSOs ($>$0.001 $M_\odot$ yr^{-1}) by constraining their SEDs. Only a minority of the sample, 30%, coincided with H II regions that are usually ultra- or hyper compact. The latter was also confirmed by Sánchez-Monge et al. (2011) and Sewilo et al. (2011). Indeed the majority of 6.7 GHz masers seems to appear before the H II stage of MYSOs, as was suggested by earlier studies, e.g., Walsh et al. (1998). Alternatively, we may still not have been able to reach the proper sensitivity for such conclusions.

Studies of specific sources in multiple maser transitions and their counterparts in other tracers are of special value. In the well known ON 1 source OH transitions at 1.612, 1.665, 1.667, 1.720, 6.031 and 6.035 GHz lie in a similar region as 6.7 GHz methanol masers. Green et al. (2007) concluded that they possibly trace a shock front in the form of a torus/ring around the YSO. That interpretation is also supported by polarization angles and velocity gradients. In the HMSFR NGC 7538 IRS 1 new masers at 12.2 GHz were found (Moscadelli et al. 2009) and in addition, 23.1 GHz Class II methanol masers were accurately registered (Galván-Madrid et al. 2010). They appear closely associated with 4.8 GHz H_2CO masers, indicating that the conditions must be similar for both of these relatively rare masers. It is possible that they are excited by the free-free emission from an H II region. However, surprisingly, they are not accompanied by any 6.7 or 12.2 GHz methanol masers.

Although we are collecting more and more information, the origin of maser structures in high-mass star formation is still not clear. A long-term question *what do linearly distributed methanol masers trace, an edge-on disc or an outflow?* is still open. De Buizer et al. (2009) showed that orientations of SiO outflows were not consistent with the methanol masers delineating a disk orientation. Moreover, for the methanol rings the proposed morphology could generally not be confirmed by infrared high resolution imaging (De Buizer et al., these proceedings). Beuther et al. (2009), using NH_3 as a tracer towards methanol Class II masers found that if Keplerian accretion disks exist, they should be confined to regions smaller than 1000 AU. Therefore, ALMA-resolution observations are really needed in order to reach the relevant scales in the direct environment of MYSOs.

5. Masers as a signpost of star formation

Masers are readily usable as a diagnostic in complex SFRs, for example as indicators that star formation has begun. Purcell et al. (2009) investigated the NGC 3576 region and verified the evolutionary status of the various molecular components. Water masers were found towards the NH_3 emission peaks, lying in the arms of the filament. In the HMSFR G19.61−0.23 water masers trace the outflow/jet associated with the most massive core, SMA 1, also traced by $H^{13}CO^+$ emission (Furuya et al. 2011). The massive cold dense core G333.125–0.562 showed water and methanol masers, as well as SiO thermal emission, but remained undetected at wavelengths shorter than 70 μm (Lo et al. 2007). Moreover, 44 GHz methanol masers coincide with presumably masing 23 GHz NH_3 emission in the EGO G35.03+0.35 (Brogan et al. 2011). The latter project is based on simultaneous observations of continuum emission and a comprehensive set of lines, something that has become possible with the Expanded Very Large Array (EVLA) and should contribute significantly to our understanding of star formation (Brogan et al., this volume).

6. Variability of masers

The 6.7 and 12.2 GHz methanol masers have been monitored and unexpectedly periodic variations were discovered from some masers in HMSFRs (e.g. Goedhart et al. 2003). Such studies are possible with single-dish observations and often require long-term commitments. Monitoring can provide important clues about which phenomena are responsible for the variability, but also about the more general physical conditions in the masing regions or the background radiation field.

Recently, Goedhart et al. (2009) summarized nine years of monitoring of G12.89+0.49 at the 6.7 and 12.2 GHz transitions and suggested that the stability of the period is best explained by assuming an underlying binary system. In G9.62+0.20E three methanol lines at 6.7, 12.2 and 107 GHz showed flaring (van der Walt et al. 2009) and a colliding-wind binary (CWB) scenario is found to explain periodicity through variations in the seed photon flux and/or the pumping radiation field (van der Walt 2011). Follow-up studies were required in order to provide more details about the source; VLBI imaging revealed the maser distribution (Goedhart et al. 2005) and multi-epoch observations enabled the direct estimation of its distance of 5.2±0.6 kpc via trigonometric parallax (Sanna et al. 2009). Recently, Szymczak et al. (2011) discovered a similar case of variability in G22.357+0.066 that can also be explained by changes in the background free-free emission. A period of 179 days was derived from single dish monitoring. The time delays seen between maser features can be combined with the VLBI imaging to construct the 3D structure of the maser region. Another example is G33.641−0.228 where the 6.7 GHz methanol bursts originate from a region of 70 AU (Fujisawa et al. 2012). The authors interpret this as coming from an impulsive energy release like a stellar flare. By monitoring many different objects we may also find more newly appearing masers as was the case with 6.7 GHz emission in IRAS 22506+5944 (Wu et al. 2009).

Variability was also detected for other maser transitions. In G353.273+0.641 intermittent 22 GHz maser flare activity appeared to be accompanied by structural changes, likely indicating that the excitation is linked to an episodic radio jet (Motogi et al. 2011b). Lekht et al. (2012) presented a catalog of 22 GHz H_2O spectra monitored over 30 years towards G34.3+0.15 (aka W44C). They detected a long-term variability with an average period of 14 years and two series of flares that are likely associated with some cyclic activity of the protostar in the UC H II. 1720 MHz OH masers towards W75N also showed flaring, possibly related to the very dense molecular material that is excited and slowly accelerated by the outflow (Fish et al. 2011a). A surprising event was registered in IRAS18566+0408 by Araya et al. (2010): the 4.8 GHz H_2CO maser showed flaring and a period correlated with the 6.7 GHz methanol outbursts. Both regions are separated spatially, so both phenomena likely indicate variations in the infrared radiation field, maybe related to periodic accretion events.

7. Masers in low and intermediate-mass protostars

Because low and intermediate-mass stars are more common and evolve more slowly, they should in principle be easier to study, at closer distances, maybe less embedded and in less confusing environments. It should therefore be possible to study the star-formation process in more detail. However, masers are not so common in these kinds of objects and appear possibly in different stages. Bae et al. (2011) found that only 9 and 6% of a sample of 180 intermediate-mass YSOs showed 22 GHz water and 44 GHz methanol maser emission, respectively. Water is likely related to the inner parts of outflows and can be highly variable, while methanol is possibly associated with the interfaces of the outflows with the ambient dense gas. The detection rates of both masers rapidly decreases as the central (proto)stars evolve and the excitations of the two masers appear closely related. The most embedded (Class 0-like) intermediate-mass YSOs known to date are all associated with water masers (e.g., Sánchez-Monge et al. 2010; de Oliveira Alves, these proceedings). However, an intriguing object, IRAS 00117+6412 was found with water masers in MM2, where no outflow seems present (Palau et al. 2010). In order to understand this case, more observations with the best sensitivity and resolution are needed.

The 44 and 36 GHz Class I methanol masers rarely appear in lower-mass YSOs. Kalenskii et al. (2010a) found only four 44 GHz and one 36 GHz maser, while no emission was detected towards the remaining 39 outflows. They also noticed the masers have lower luminosity compared to those in HMSFRs. Imaging of L1157 indicates that the 44 GHz maser may form in thin layers of turbulent post-shock gas or in collapsing clumps (Kalenskii et al. 2010b; Kalenskii et al. these proceedings).

8. HMSFRs in the Galactic Centre and beyond the Galaxy

Recent searches towards Sgr A revealed that the 36 GHz Class I methanol masers correlate with NH_3(3,3) density peaks and outline regions of cloud-cloud collisions, maybe just before the onset of local massive star formation (Sjouwerman et al. 2010a). The 44 GHz masers correlate with the 36 GHz locations, but less with the OH masers at 1720 MHz (Pihlstöm et al. 2011a), which are associated with the interaction between the supernova remnant Sgr A East and the interstellar medium (Pihlstöm et al. 2011b). One particularly interesting group of 44 GHz masers was found that does not overlap with any 36 GHz emission. These masers may signal the presence of a hotter and denser environment than the material swept up from the shock, maybe related to advanced star formation (Pihlstöm et al. 2011a).

Kilomasers are masers beyond our Galaxy, with luminosities comparable to the brightest galactic maser, which either amplify a background AGN or originate from star-forming regions. These Galactic analog H_2O masers have become a great tool in studies of young super-star cluster formation with high angular resolution. They are detected in a few nearby galaxies only (e.g., Castangia et al. 2008). Brogan et al. (2010) found that water masers in the Antennae Galaxies are associated with star-formation, as they show kinematic and spatial agreement with massive and dense CO molecular clouds. The various early stages of star formation in the components of the Antennae Galaxies was confirmed by Ueda et al. (2012).

The Large and Small Magellanic Clouds were also searched for maser emission. Green et al. (2008) detected four 6.7 GHz methanol (of which one is new) and two 6.035 GHz OH (of which one is new) masers in the LMC. Both transitions indicate much more modest maser populations compared to the Milky Way, likely originating from lower oxygen and carbon abundances. Moreover, Ellingsen et al. (2010) found the first 12.2 GHz methanol maser towards the LMC. They also detected 22 GHz water and 6.7 GHz methanol masers that are associated with more luminous and redder YSOs. The first 6.7 GHz methanol spectrum towards Andromeda Galaxy (M31) was presented by Sjouwerman et al. (2010b). More on kilo- and also mega-masers is presented by e.g. Tarchi (these proceedings).

9. Magnetic field

Masers are a particularly unique tool for studying the magnetic field studies in HMSFRs (Vlemmings, these proceedings). This is an important subject in star formation, as the magnetic field could be a dominant force in the process by supporting the molecular cloud against gravitational collapse, regulating the accretion and shaping the outflows as has been argued for Cepheus A (Vlemmings et al. 2006). We have already mentioned the work by Green et al.(2007) who found a shock front in the form of a torus/ring around the YSO in ON 1. That scenario is also supported by the measured polarization angles of the masers. A magnetic field strength of a few mG was detected through the Zeeman splitting of OH and methanol masers. Linearly and circularly polarized emission of 22 GHz water masers was used for measuring the orientation and strength of magnetic fields in W75N. The magnetic fields around the young massive protostar VLA2 are found to be well ordered around an expanding gas shell (Surcis et al. 2011b). In NGC 7538–IRS 1 the water masers did not show significant Zeeman splitting while the 6.7 GHz methanol masers indicated a possible range of magnetic field strength of 50 mG $< |B_{||}| <$ 500 mG, depending on the value of Zeeman-splitting coefficient. These masers likely are related to the outflow and the interface between infall and the large-scale torus, respectively (Surcis et al. 2011a).

10. Summary

It is clear that many new results and discoveries have been obtained in our attempts to understand star formation and the associated masers. Are we closer to answer the key-questions? What is the current state of masers in SFRs?

We note, that:

- The time sequence for masers seems to take shape and is confirmed by (most) new methanol transition measurements, however, some issues still exist,
- Convergence can be seen on the issue where water, methanol (both Classes), OH and SiO arise, but testing the hypotheses with high-resolution observations and at other wavelengths is critical,
- One may hope that in synergy with ALMA the role of masers to study small scale dynamics will be strengthened,
- Monitoring programs are starting to give important clues about co-evolving binaries,
- There should be more focus given to low-mass stars,
- More work on models to get accurate physical conditions is needed.

We started the review with the popular statement that *masers are an unique tool in star-formation studies* and in the end we are more convinced that they really are.

In order to advance the use of masers and solve the detailed questions we *just* need better instruments and of course the patience to work on data to obtain more and more interesting and even surprising results. We all can wait (and work) with curiosity for the further discoveries that will be presented in the next maser symposium.

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