Astrophysical Masers:
Unlocking the Mysteries of the Universe
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Conference Summary

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Abstract. IAU Symposium 336, Astrophysical Masers: Unlocking the Mysteries of the Universe, took place between 4 - 8 September, 2017 in Cagliari, on the beautiful island of Sardinia. The Symposium, the fifth focusing on masers as a tool for astrophysics, was dedicated to our friend and colleague Malcolm Walmsley, who sadly passed away shortly before the meeting. To quote Karl Menten: "Malcolm made numerous fundamental contributions to our understanding of the physics and chemistry of star formation and the interstellar medium. He was an exceptional scientist, a highly esteemed colleague and a true gentleman". Vale Malcolm.

The topics discussed at the symposium covered a huge range, from star-formation, evolved stars, galaxies and their constituents, super-massive black-holes to cosmology.

1. Introduction

The previous symposium in the series (IAUS 287; Booth, Vlemmings & Humphreys 2012) took place in Stellenbosch, South Africa, five years ago; looking back on the topics covered then, they were broadly similar to those discussed in Cagliari but with important and major differences. First, we are seeing the culmination of major, long-term monitoring programmes; secondly, we are seeing the massive impact of ALMA and the JVLA; thirdly, it is clear that GAIA is a game-changer for galactic science; and, finally, the panchromatic information that is now available is enabling a much deeper view of the physical conditions and overall environments in which masers exist than was previously available. And, it is only going to get better.

This summary will not describe every paper presented but will be a personal view of the key advances since the Stellenbosch meeting. In the text below, when referring to the work of colleagues I will, in general, reference the papers from this meeting, except where this is inappropriate.

The Scientific Organising Committee had arranged for several broad reviews, which were uniformly excellent and set the scene and the context for the conference papers. Karl Menten kicked off the meeting with a review of *50+ Years of Maser Research*, this described the state of the art in maser astrophysics prior to this Symposium. Christian Henkel summarised the current situation with surveys of extragalactic masers (Henkel, Greene & Kamali 2018), while Till Sawala provided an excellent review on the Local Group from a perspective outside of radio astronomy. As the meeting focused on the structure of the Milky Way as revealed by maser observations, Ortwin Gerhard set the scene with a review of galactic structure, again from a broader perspective (Gerhard 2018). The two final reviews covered both the birth of stars (Beltran 2018) and the end of their lives, the latter was presented by Perrin.

2. Key advances

Extragalactic Megamasers. The Megamaser Cosmology Project (MCP) is a multi-year VLBI project with the aim of measuring the Hubble Constant through the determination of the geometric distances to circumnuclear 22 GHz H_2O megamasers in galaxies within the Hubble flow. Braatz, on behalf of the MCP team, presented the latest results of this key project (Braatz *et al.* 2018).

178 galaxies are currently known to host H_2O megamasers; their detection rate peaked in the years 2006-2009, with the majority of recent discoveries being made with the Green Bank telescope. Of the 37 megamasers known to be in disk galaxies, 10 have been targeted for distance measurements with a global, highly-sensitive VLBI array. Four galaxies have had their distances measured to date, the current estimate of H_O from those galaxies is 69.3 ± 4.2km s^{-1} Mpc^{-1}. The MCP team expect to determine the distances of five more galaxies in the next year and should achieve a total uncertainty of $\sim 4\%$.

The detection rates of H_2O megamasers from carefully designed surveys has been quite low, typically $\sim 15\%$. However, in two separate papers, Zhang *et al.* (2018) and Panessa *et al.* (2018) have experimented with different selection criteria, namely Seyfert 2 galaxies, and galaxies selected through their hard X-ray emission, respectively. The detection rate from a complete sample approximately doubled, which is encouraging for the future.

There has been surprisingly little progress over recent years in our understanding of OH Megamasers (OHM). The principle result reported at this meeting was the study of OHM magnetic fields reported by Robishaw. 77 OHM have been searched for evidence of Zeeman splitting, 14 have been detected, with a median magnetic field strength of 12mG. To date, little polarization-sensitive VLBI imaging has been conducted so the structure of the magnetic fields remain obscure.

The Structure of the Milky Way. The study of galactic structure through astrometric measurements of the parallax of masers has been one of the highlights of the field over most of the last decade. Two projects, the VLBA key science project, BeSSeL, reported on by Reid (2018) and its equivalent being undertaken with VERA in Japan, reported on by Honma *et al.* (2018), have both been magnificent success stories and have significantly improved our understanding of the size and structure of the Milky Way.

These projects are delivering results at the same time as the ESA satellite GAIA is flying. As reported by Mignard on behalf of the GAIA team, GAIA will determine parallaxes and proper motions for over a billion stars, with associated accurate photometry. With such an enormous database, GAIA will provide a superb view of the structure of the Milky Way in the optical domain, which will provide a highly complimentary picture to that determined through the maser astrometry.

Surveys. Recent improvements in technology and in the capabilities of observing facilities have resulted in a renaissance in surveys of maser sources. I'd like to call out a few specific examples, a list which does not pretend to be complete. Breen, in an invited talk, described the current status of recent southern hemisphere maser surveys (Breen 2018). Two major surveys have been the Methanol Multi-Beam (MMB), which also has a northern hemisphere component, and MALT45, a survey for mm-wave masers. The MMB has detected almost 1000 6.7GHz methanol masers within the galactic plane; like most similar surveys, there have been numerous spin-off projects, many of which have themselves resulted in interesting science and new discoveries. MALT45, an ATCA legacy survey, is observing 90 square degrees of the Southern galactic plane at 7mm, searching for Class 1 methanol masers, SiO masers and recombination lines.

A fascinating new survey is BAADE, which was reported on by Sjouwerman *et al.* (2018). BAADE is a survey of $\sim 34,000$ AGB/RGB stars in the galactic plane and

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bulge for SiO masers with the JVLA and ALMA. The principal aim of the survey is to significantly improve models of the dynamics and structure of the inner Galaxy, through the use of the stellar masers as radio-detected point-sources. The current status is that all of the JVLA data has been taken, the ALMA data acquisition is underway and pilot follow-up VLBI observations with the EVN, VLBA and VERA have been undertaken.

Star Formation Masers. As is by now normal in any maser symposium, a large fraction of the talks and posters are focused on increasing our understanding of the physics of star-formation as revealed through maser observations. The basic evolutionary sequence for high-mass star-formation, which has been obscure for many years, now seems to be yielding to the weight of observation. In his review, Menten discussed that time sequence in broad terms, which sees H_2O masers associated with the earliest stages, then Class II radiatively pumped CH_3OH masers, followed by OH maser emission.

CH_3OH featured in a major way at this meeting, with 21 talks and numerous posters discussing both Class I and Class II masers. As mentioned above Class II sources are strongly associated with regions of high-mass star-formation, whereas Class I masers are well-known to be associated with outflow sources.

Evolved Stars. Another old favourite for attendees at maser symposia is the now traditional session on evolved stars, and area in which I declare an interest lasting almost 30 years. Imai provided an excellent invited talk describing the rationale behind multi-year, indeed multi-decadal, single dish and VLBI monitoring of circumstellar maser sources. He pointed out that long-term VLBI monitoring of such sources is essential for our understanding of the mass ejections processes and the nature of the environments around AGB stars (Imai 2018).

One particular source highlighted by Imai in his talk was the water fountain in W43A. He and his colleagues, of which I am one, had previously proposed that the water jet we had observed was the result of a precessing jet and had a very short dynamical age. However, new results suggest that the H_2O structures seen are in fact the result of discontinuous ejection of a jet and its interaction with the walls of a previously excavated cavity; this changes the physical nature of the system.

Imai draws attention to the 28 talks and posters which refer in one way or another to observations of masers in evolved stars, a number too large for me on which to provide appropriate attention. The large number does, however, demonstrate that this is still an area of active and advancing research.

3. Conclusions

The Symposium was an excellent week of science, networking, food and drink in a beautiful part of Italy. The meeting was capped with a visit to the Sardinia Radio Telescope, which is now operational. On behalf of all the attendees, I thank the Local Organisers for all their hard work.

Maser research, our subject, is in rude health. The science progress since the Stellenbosch meeting in 2012 is clear and exciting. Although there is some concern about the long-term funding for one of the keystone facilities, the VLBA (or LBO), the loss of which would be catastrophic for maser and other high-resolution astronomy and astrometry, new or upgraded instruments such as ALMA and the JVLA are demonstrating their power. The future on that front is also truly exciting, with instruments such as MeerKAT, ASKAP and ultimately the SKA becoming available.

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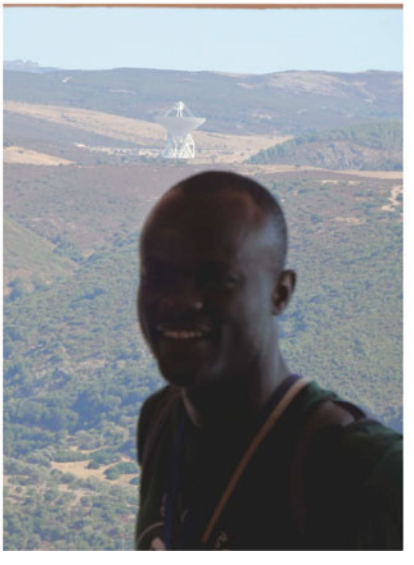


Top row: Anna Bartkiewicz, Liz Humphreys, Ylva Pihlstrom, and Alison Peck in front of the Sardinia Radio Telescope (left); Symposium participants in a wood of ancient oak trees standing close to a menhir while listening about the prehistory of Sardinia (right) Mid row: Alberto Sanna and Anna Bartkiewicz (left); LOC members Tiziana Coiana and Paola Castangia, satisfied of the Symposium outcome (right) Bottom row: a group of participants (from left to right: Tomoya Hirota, Ciriaco Goddi, Jan Brand, and Gordon MacLeod) discussing at the end of a Symposium session (left); James Chibueze enjoying the view of the Sardinia Radio Telescope and the Gerrei area (right)

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