Chapter 8
Concluding Remarks

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Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Closing Remarks of the International Astronomical Union Symposium 380

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Abstract. We are pleased to summarise the IAU Symposium 380, *Cosmic Masers: Proper Motion toward the Next-Generation Large Projects* held on March 2023 March 20-24 in Kagoshima City, Japan. It is the sixth symposium focusing on astrophysical masers broadly used in research of star formation and evolved stars, astrometric measurements of the Milky Way galaxy, as well as studies of extragalactic environments.

Keywords. Masers, Milky Way galaxy, Extragalactic

1. Introduction

For the first time, the cosmic maser meeting series was held in hybrid mode gathering in total more than 172 participants; 70 online and 102 in-person admiring Kagoshima city and Mt. Sakura-jima – an active stratovolcano. In total, we represented 28 countries counted by the location of the main institute affiliation of each participant. This sixth astrophysical maser symposium finished the "continent cycle" (North America, South America, Australia, Africa, Europe, and Asia) which began with the first symposium taking place in USA (1992), followed by meetings in Brazil (2001), Australia (2007), South Africa (2012), and Italy (2017). The IAUS maser meetings are recurrent approximately every 5 years, and we can therefore be considered to be super-periodic considering the conference locations! This pattern will be analysed in more detail at the proper time.

In his closing remarks of the 2017 IAUS 336 in Cagliari, Italy, Prof. Phil Diamond stated (Diamond 2018): *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.* It is clear that after six years significant progress has been made in all aspects of maser astrophysics, and in particular ALMA and Gaia have made deep impacts. As evidenced by the results reported on in these proceedings, ALMA served the wide astrophysics community as a supplier of maser as well as counterpart data with high-sensitivity and high-angular resolution, covering topics from planetary nebulae, star-forming regions, to Ultraluminous Infrared Galaxies (ULRIGs). The access to Gaia DR3 has enabled cross-checking opportunities for maser astrometry projects (e.g., Quiroga-Nunez†). While in many cases the Gaia parallaxes

† When none citation is given, we link the proceedings from this volume by the name of a speaker/first author

markedly enhance the scientific output through distance estimates, during the meeting it was emphasised that for evolved stars Gaia parallaxes need to be treated with caution due to the obscuration at optical wavelengths.

Seven major topics on maser sciences were presented and discussed: theory, cosmology, galaxies, Milky Way, star-formation, evolved stars, and future projects. Just as in previous meetings, the details of high-mass star-formation (HMSF) continues to stimulate extensive research through primarily methanol and water maser studies. The importance of monitoring programs over more than 10 years using mid-sized antennas was stressed, as it has enabled new discoveries in the regime of maser variability. The flare spectra and light curves may indicate the underlying mechanisms of the variability. Houde proposed that superradiance is responsible for the fast variability, while Gray pointed out effects like catastrophic release of saturation capable of causing fast intensity variations at a given velocity. The new and strongly time-dependent features reported thus encourage the community to continue, or to start, monitoring programs with frequent sampling for a diverse set of maser transitions. Progress has also been made in understanding the polarization of masers. Lankhaar further expressed the need for 183 GHz galactic and extragalactic water maser observations.

2. New insights from maser research

In recent years, accurate Galactic astrometry has been done and the Milky Way rotation curve has been verified (e.g., Rygl, Honma, Reid, Ellingsen). It is clear that we now can study the "unreachable" – e.g., the Bulge (Sjouwerman, Lewis), the Long Bar (Kumar), the Galactic Centre (Paine, Sakai), and we can learn about kinematics in extremely obscured LIRGs (e.g. Aalto). New hypotheses were posed to be verified in the futur: *1) Has the gap in the Perseus-arm originated in a cloud collision?* (Sakai), and *2) Do kilomasers indicate supermassive stars?* (Nowak)

Concerning HMSFRs, in this volume we find multiple new close-ups providing milliarcsecond details of individual star-forming regions like the discovery of the magnetohydrodynamic disc wind in IRAS 1078+5211 (Moscadelli), the 3D structure reconstruction of masing regions in periodic methanol masers (Olech), the magnetic field estimation at a few 100s AU scale using 6 GHz OH masers (Kobak), and tracing rotation of magnetic field in W75N (Surcis).

Since the 2017 maser meeting high-resolution observational results have also been added for evolved stars, for example the VLBI results presented on OH/IR (Nakagawa). We observe wind motions in circumstellar envelopes (CSE) of red-supergiants (RSG) (Brand), and they are a signpost of transitional phases along the Asymptitic Giant Branch (AGB) shell (Etoka). Water fountains also have been found to contain SiO masers (Amada, Uscanga).

In the cosmology domain, we are closer to resolving the Hubble tension problem (e.g. Pesce, Kuo, Nakai) where the water megamaser project plays a role. Detailed kinematics of Acitve Galactic Nuclei (AGN) is possible (e.g. Impellizzeri, Nakai).

Finally, new maser species and transitions were discovered: a methanimine maser at 5.29 GHz (Xue) and mm methanol maser transitions (Brogan).

3. The power of teams

Considering the relatively small number of researchers in the cosmic maser community, it is important to appreciate the worldwide efforts under collaborations such as M2O (www.masermonitoring.com), GASKAP–OH (gaskap.anu.edu.au), BeSSeL (bessel.vlbi-astrometry.org), and BAaDE (leo.phys.unm.edu/~baade/). These teams aim to examine the outbursts at the cm maser transitions in the time and frequency domain by combining

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results from a diverse set of instruments, to provide astronomers with an unprecedented view of the neutral gas content of the Milky Way and nearby Magellanic system via H I and OH line observations, to estimate parallaxes to methanol and water masers in HMSFRs to discover the structure of the Milky Way, to map the positions and velocities of up to $\sim 30,000$ evolved stars via SiO masers along the full Galactic plane, respectively. These are ambitious project goals that can only be achieved through team efforts.

4. New capabilities and Challenges for future

New instruments always open up for new research programs. We gleaned results from SKA precursors as ASKAP and MeerKAT. New OH megamasers were discovered and we may expect more progress in our understanding of these systems (Glowacki, Roberts). Hopefully, in the next symposium, we will see the first results from the Italian INAF radio telescopes and from the Nobeyama 45-m radio telescope that are about to be equipped with new receivers. We also look forward to access data from the extended Korean VLBI Network and 40-m Thai National Radio Telescope.

Despite the new monitoring programs, time-sampling of masers on a larger scale still is a challenge, requiring substantial amounts of telescope time. We still need multi-epoch and multi-frequency observations to see details and to infer physical conditions of obscured regions from where we can detect masing clouds: interiors of star-forming regions and environments around evolved stars. The maser community also plan to do further astrometry to obtain more accurate measurements at the μas level including parallax estimation of long-period OH/IR stars since Gaia will not be able to probe the optical emission from their obscured central stars. A noted challenge is to obtain more parallaxes in the 3$^{\rm rd}$ and 4$^{\rm th}$ quadrants, and therefore Australia – New Zealand VLBI is requested.

Science questions raised during the Symposium include: *Are water fountains common and are they periodic?* (Imai), *What are the longest and shortest periods of periodic methanol sources?* (Olech, Tanabe, van den Heever, Kenta), and *What is the mass-loss history in evolved stars?* (Yun). To find answers to these questions, high-sensitivity surveys are requested for water megamasers (Castangia) and gigamasers (Pesce, Kuo). Similarly, increased sensitivity is needed for research of sub-mJy water masers in HMSFRs and radio-continuum counterparts (Sanna). There are hopes that ngVLA will help with at least some of the above challenges.

5. Summary

The Symposium was an amazing (a-masing!) opportunity to catch up on the newest science that has been done in last years, including during the difficult time of 2020-2022, when the pandemic time due to the COVID-19 forced our community to be separated. However, the science progress since the Cagliari meeting in 2017 is remarkable and exciting. The first results from MeerKAT and ASKAP have been presented, and we wait for more: from SKA and the upgraded ALMA. However, we need to keep operating the single-dish telescopes, especially mid-sized, as they have proven crucial for monitoring programs.

On behalf of all the attendees, in person and online, we thank the Local Organisers and 14 young volunteers for all their hard work before the Symposium and during it. We acknowledge the social program with the excursion to a black vinegar factory at Kakuida Black Vinegar and Arimura Lava Observatory to have a view for Sakura-jima volcano and Kinko-wan Bay. Also, the banquet that took place in The Peak Premium Terrace in Tenmonkan area, was enjoyable time with delicious food and dances. This IAUS gathered the largest number of speakers, the idea of flash-talks should be continued. It was a

great opportunity for younger researchers to meet in person "more advanced/evolved" colleagues and start collaborations since the power of maser studies is crossing borders - national and institutional.

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Reference

Diamond, P.J. 2018, *Astrophysical Masers: Unlocking the Mysteries of the Universe*, Proc. IAU Symposium No. 336, p. 451-454

Group photo of the volunteer staff. From left to right, Anna Bartkiewicz (speaker of the concluding remarks), Hiroshi Imai and Akiharu Nakagawa (LOC co-chairs), Yuichi Sakamoto, Tatiana M. Rodríguez, Kaito Kawakami, Ryosuke Watanabe, Yosuke Shibata, Koki Tanaka, Kei Amada, Rina Kasai, Keisuke Nakashima, Daisuke Takaishi, Jayender Kumar, Nao Ikeda, Ka-Yiu Shum, and Roldán A. Cala. Taken by Tomoya Hirota.

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