PROCEEDINGS OF SCIENCE

Recent updates on the Maser Monitoring Organisation

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The Maser Monitoring Organisation (M2O) is a research community of observers, astronomers and theoreticians pursuing a joint goal of reaching a deeper understanding of maser emission and exploring their variety of uses as tracers of astrophysical events. These proceedings detail the origin, motivations and current status of the M2O, as was presented at the 2021 EVN symposium.

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1. The Maser Monitoring Organisation

Maser emission has long been used as an observational tracer of activity in astrophysical contexts, from solar system bodies, stellar births, stellar deaths and the disks of distant supermassive black holes. Their extreme brightness temperatures make them readily detectable by observational instruments, their narrow spectral line-widths make them excellent tracers of dynamical processes, additionally, knowledge of the required conditions of local densities, temperatures and radiation environments in which they arise make them effective indicators of physical conditions. Unsurprisingly, maser observations have contributed to an eclectic mix of topics in astronomy.

Maser emission is very sensitive to its environment; a change in physical conditions and the presence/lack of shocks can selectively favor or unfavor the pumping/sink mechanism of different maser transitions, effectively switching them *on* or *off*, or causing temporal variations as the local environment approaches or deviates from what is required to produce maser activity. This selectivity of masers results in specific transitions often found being found to associate with, and thus trace, specific astrophysical environments and structures; the 6.7 GHz methanol maser typically associates with high-mass protostellar disks, and the 22 GHz water maser typically associates with shocks in proto-/stellar jets. Multi-epoch radio observations of multiple maser species and transitions can thus locate disks, shocks, outflows and other structures in deeply embedded systems that are otherwise inaccessible to observation, in addition to tracing their evolution.

Many radio observatories conduct long-term monitoring of masers either as a main internal programme, via open-use proposals, or in the available time between PI-driven science observations, all in efforts to track flux variations. In addition to discovering periodic masers this way, monitoring programs have identified flare events where fluxes suddenly rises several orders of magnitude above their usual values, often indicating the occurrence of an energetic astrophysical event. In a case of extremely fortunate timing, during the IAUS 336 symposium on astrophysical masers in September 2019 reports surfaced of two large maser flares in high-mass star forming regions G25.65+1.05 and W49N. News of these events quickly became popular focal points at coffee breaks and ultimately the timely gathering of maser experts and observers facilitated the organisation of immediate requests of directors' discretionary time for follow-up maser imaging observations with several VLBI arrays. Presenters at the symposium had also reported several past maser flares witnessed in their monitoring campaigns, but had not been followed up at the time - an opportunity thereby missed since such flares proved to be short-lived. In light of the need for prompt and organised follow-up responses to maser flares, and in the excitement of the G25.65+1.05 and W49N events, the Maser Monitoring Organisation (M2O) was established during an interlude between talks. Its initial goal was of providing a communications platform where monitoring stations could report new flare events that could then be confirmed by other radio observatories, and followed up using VLBI observations. Activities since then have rapidly expanded beyond this initial scope.

2. M2O: General operation

In practice, and at its core, the M2O is a communications platform which connects radio observatories with each other, with follow-up facility users, with maser theorists who contribute knowledge of maser production and behaviour, and with experts of various astrophysical systems,

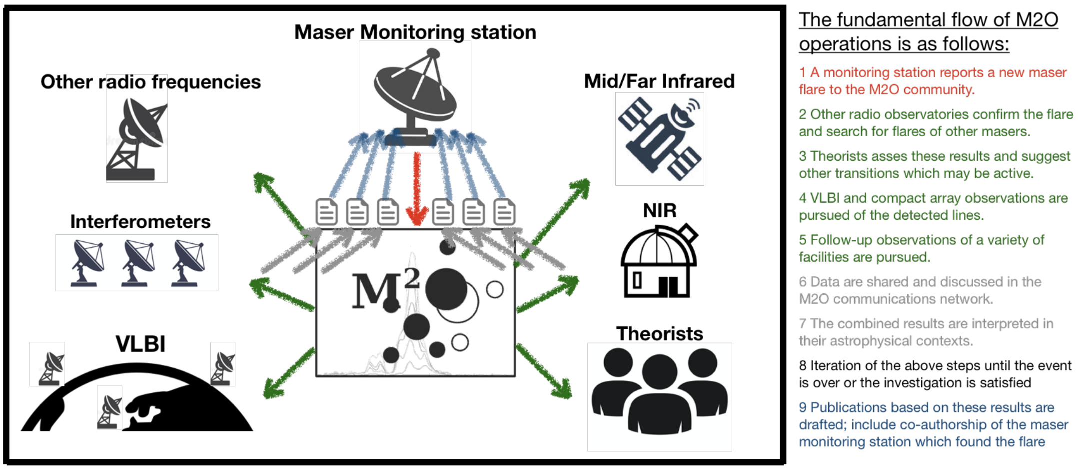

Figure 1: General flow of an M2O response to a new maser flare, coloured arrows match coloured text

such as star forming regions, who consider the available information in the context of its environment. Observational resources acquired for use in quick-response follow-ups are available and their use determined collectively by the community, in that if a maser flare event appears to be interesting then a proportional investment of resources is undertaken. This can range from zero to up to around 100 hours across many facilities as was the case for G358.93-0.03 (see below). Furthermore, the monitoring station that reports a maser flare event is given acknowledgment via their inclusion in all subsequent publications, as thanks, since without such reports there would be nothing to follow-up in the first place. Prompt communication of flare alerts and the sharing of information and observing resources seems to have been key to the recent success of the M2O.

3. The G358.93-0.03 maser flare

The G358.93-0.03 maser flare event and follow-up campaign became the first large-scale and focused flare pursuit of the M2O into which more than 20 follow-up observing requests were invested. G358.93-0.03 is a high-mass star forming region in the Galactic centre direction, which was first identified by its 6.7 GHz methanol maser emission. This maser had been monitored by the Hitachi 32-m radio telescope team operated by Ibaraki University, who reported maser flare activity to the M2O on the 18th of Jan 2019. Tracking the evolution of the 6.7 GHz methanol maser transition showed that the burst reached peak brightness some 70 days later [1] followed by a brightness reduction over ~ 4 months, at which time the main flare phase appeared to have subsided.

Follow-up ALMA observations revealed a cluster of 7 millimeter cores, of which G358-MM1 was identified as the progenitor of the maser flare. It exhibited hot core chemistry and spatio-kinematics indicative of rotation [2] and spiral-like substructures [3]. During the flare state, high-resolution imaging of the 6.7 GHz methanol maser revealed a 'heat-wave' of accretion energy propagating outward from G358-MM1 at subluminal speeds [4]. Measurements of the pre-, mid- and post-burst phase infrared spectral energy distribution enabled by SOFIA observations concluded that G358-MM1 gained $M_{acc} = 5.3^{+11.1}_{-4.4} \times 10^{-4} M_{\odot}$ of mass during the accretion burst

[5], and independent agreement was obtained for estimates of the stellar mass ($\sim 9M_{\odot}$) and system inclination (22 degrees from face-on) in analyses of dynamics traced by spectral line data with the VLA [3] and ALMA [2], and in infrared radiative transfer modelling analyses [5]. At the time of writing 27 new maser transitions have been discovered in association with the accretion burst whose utility as possible new astrophysical tracers is now being explored [1–3, 6, 7] The M2O-led investigations into G358-MM1 produced to what is at present the most recently identified, and most intensely studied accretion burst event of a high-mass protostar. More results from G358-MM1 and other targets are in preparation.

4. Current Status of the M2O: Membership, Flares, Publications, Resources

The M2O currently has 80 members, spanning Europe, Asia, the Americas and Australasia, and includes individuals at all levels of academic progression from students, through postdocs and professors, to directors of research institutes. To date, 15 flares have been reported to the M2O, comprising events identified by seven flares of 6.7 GHz methanol masers and eight 22 GHz water masers. Follow-up campaigns were initiated for 12 of these flares, of which 6 targets have generated publications: W49N, G25.65+1.05, G358.93-0.03, G24.33+0.14, G359.617-0.251, IRAS16293-2422, with more on the way (see the website[1] for an up-to-date list of publications).

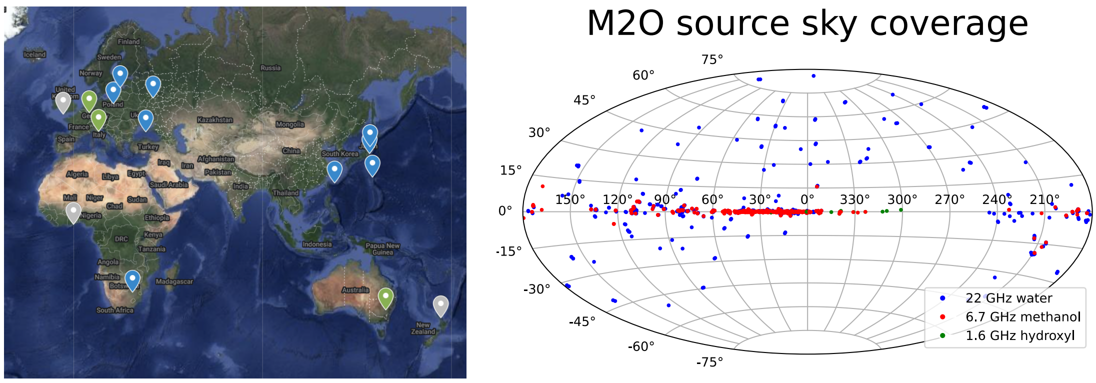

Figure 2: *Left:* Global distribution maser monitoring observatories with internal programmes (blue icons), those used as open-use (green icons), and those indicating interest in contributing in the future (grey icons). *Right:* Distribution of maser targets monitored by the cumulative of M2O participating stations.

The most vital resource of the M2O is the maser monitoring stations which search, identify and report new maser flare events by monitoring large numbers of maser targets at observing cadences typically between days and weeks. Most of the observatories' monitoring programs predate the M2O by years or even decades, as indeed the M2O is merely the collaboration of efforts amongst observatories and other maser enthusiasts. At present 9 observatories monitor as part of their internal programmes, 3 observatories are used for monitoring as part of open-use proposals, 3 more stations have shown interest in joining. These are shown in Figure 2, *left*. At present around 1000 maser targets are being monitored by the cumulative efforts of M2O monitoring stations.

[1] https://www.masermonitoring.org

Uniquenesses in hardware, latitudes and time available gives rise to an arbitrary sky coverage of targets where biases toward the Galactic plane and northern hemispheres can be seen in the 1.6 GHz hydroxyl and 6.7 GHz methanol, and the 22 GHz water masers, respectively (Figure 2, *right*).

Another important resource is access to follow-up facilities, especially those providing imaging. To facilitate rapid responses to new maser flare alerts the M2O maintains access to this resource through triggerable Target of Opportunity proposals on the VLA, SMA, ATCA, ALMA, EVN, LBA, VLBA, KaVA, EAVN, Subaru, SOFIA and the JWST. Additionally the M2O also collaborates with other large programs by sharing flare information, expertise (another key resource) and in certain conditions observational resources - with teams such as the JCMT Transients Program[2] and the KaVA Star Formation Large Program[3], driven by a shared goal of broadening the wavelength coverage of follow-up investigations into episodic astrophysical phenomena.

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