Chapter 7

New Projects and Future Telescopes

Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Overview of the Maser Monitoring Organisation

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[*] The Maser Monitoring Organisation

Abstract. The Maser Monitoring Organisation is a collection of researchers exploring the use of time-variable maser emission in the investigation of astrophysical phenomena. The forward directed aspects of research primarily involve using maser emission as a tool to investigate star formation. Simultaneously, these activities have deepened knowledge of maser emission itself in addition to uncovering previously unknown maser transitions. Thus a feedback loop is created where both the knowledge of astrophysical phenomena and the utilised tools of investigation themselves are iteratively sharpened. The project goals are open-ended and constantly evolving, however, the reliance on radio observatory maser monitoring campaigns persists as the fundamental enabler of research activities within the group.

Keywords. maser emission, M2O, radio astronomy, long-term monitoring

1. Purpose and early beginnings

Astrophysical masers are excellent tracers of physical environments due to the sensitive relationship between maser emission brightness and physical parameters such as temperature, density and collision rates (Cragg *et al.* 2005; Hollenbach *et al.* 2013). Addressing this, several radio astronomy observatories have been conducting long-term monitoring of maser emission in order to uncover changes in the physical conditions of various astronomical phenomena, as a function of time (Volvach *et al.* 2020; Gaylard *et al.* 2002; Szymczak *et al.* 2018; Yonekura *et al.* 2016; Brand *et al.* 2007; Tanabe *et al.* 2023).

In the not-so-frequent astronomical conferences centered on maser emission, the fruits of labor of long-term monitoring campaigns have been discussed, and, occasionally, transient maser flare events which occurred in their data sets are reported. Unfortunately however, many of these flares were presented long after the subsiding of the event itself when it was too late to conduct follow-up observations to gather more information about the flare and its driver. The situation, brought to light in the IAUS 336 in Cagliari, Italy 2017, was determined to be worth addressing and in doing so the Maser Monitoring Organisation (M2O) was formed, with the goal of providing a communication platform - bringing maser monitoring observatories together with teams wishing to pursue follow-up investigations of time-domain maser activity. The membership and scientific scope of the M2O has expanded well beyond its original scope. Despite this, the back-bone of all M2O activities is derived from the reporting of maser flare events from long-term monitoring campaigns of radio astronomy observatories.

2. Operations

At its core, the M2O is a communications platform connecting maser monitoring observatories with follow-up facility users, and star-formation and maser experts. This overview proceedings will walk through the typical activities and resource management considerations that the M2O follows in relation to maser flare alerts.

2.1. *Monitoring activities*

Monitoring activities are reported to the M2O from radio astronomy observatories such as Ibaraki, Torun, Irbene, Medicina, VERA, Hartebeesthoek, Simeiz and Pushchino, which have their own long-term maser monitoring campaigns and independent research targets such as monitoring periodic sources. These observatories agree to alert the M2O to transient flare events as an additional activity. On the other hand, dedicated maser monitoring activity has also been initiated as part of the M2O effort, as in the case of the Parkes (P1073) project. Additionally, some stations contribute follow-up-like flare confirmation observations and short term, intensive monitoring in response to flare alerts. Effelsberg, Warkworth and Kuntunse are in this category. 14 single dish observatories (left panel of Figure 1) are contributing to M2O activities. Their cumulative monitored source lists (right panel of Figure 1) comprise: 562 targets at the 6.7 GHz methanol transition, 260 at the 22 GHz water transition, and 65 at various L-band hydroxyl transitions.

2.2. *Flare statistics*

At the time of the IAUS 380 symposium, and since inception at the IAUS 336 symposium, the M2O has received reports of 11 flares from 22 GHz water maser sources and 8 flares from 6.7 GHz methanol maser sources. This corresponds to a discovery rate of about 1 or 2 maser flare events per year (left panel of Figure 2).

2.3. *Establishing context*

Once a flare is reported, before deciding if/how to pursue follow-up observations, it is important to establish some context about the event in order to evaluate the appropriate amount of observing resources to commit. The first source of context comes from the

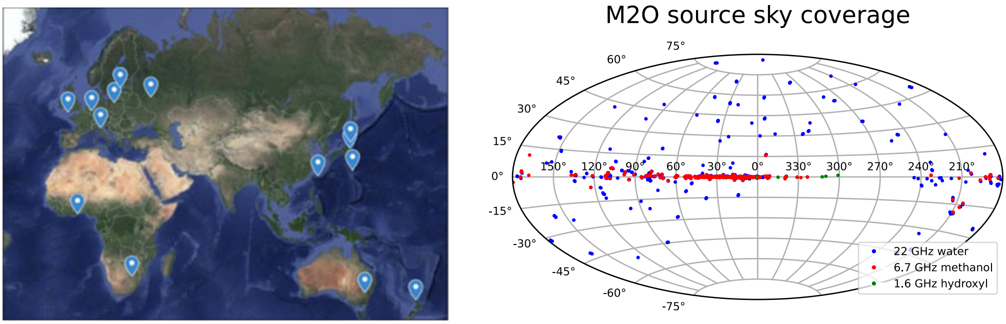


Figure 1. *Left:* Global distribution of maser monitoring observatories that have contributed monitoring data to the M2O. *Right:* Distribution of maser targets monitored by the cumulative of M2O participating stations. Up-to-date versions of these maps are accessible in the M2O website.

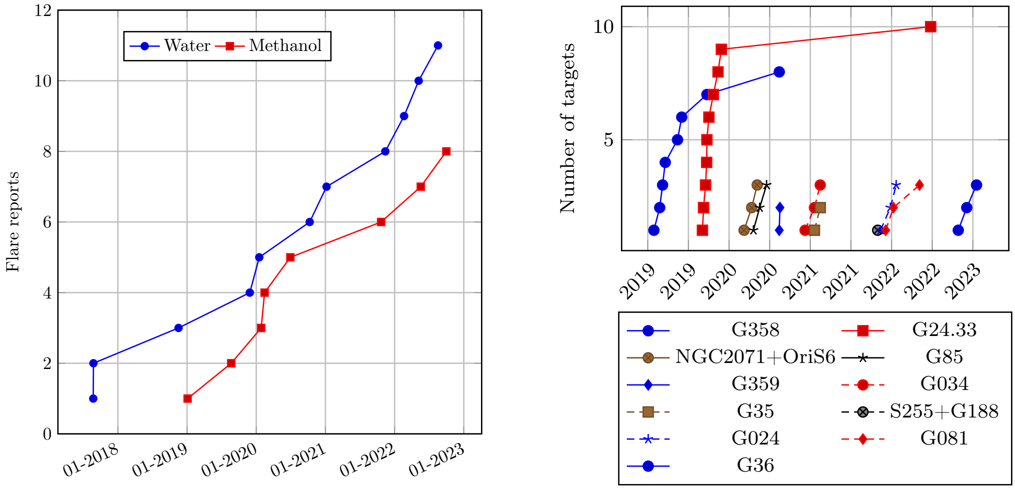


Figure 2. *Left:* Cumulative plot of the detections of 22 GHz water masers and 6.7 GHz methanol masers reported to the M2O as a function of time. *Right:* Cumulative plots of the VLBI follow-up observations conducted for maser flares in various sources.

maser itself. A rich spectrum may indicate that a large portion of the region exhibits the appropriate physical conditions to produce maser emission. Occasionally, a rich spectrum may indicate multiple progenitors within the same beam - especially telling if there are many masers at velocity separations of more than an order of magnitude, since methanol masers typically are within ~ 5 km s^{-1} of their driving source (Green and McClure-Griffiths 2011).

Temporal variations then provide an additional dimension of information. Flares of only a single velocity feature may be caused by a maser superposition (Burns *et al.* 2020a) rather than any changes in physical conditions. Enhancements in the brightness of a small fraction of the maser velocity features may indicate physical changes affecting only a small region. On the other hand, accretion bursts are identified by an increase in all maser spectral features and accompanying ignition of emission in previously empty parts of the spectrum (MacLeod *et al.* 2018a). This first evaluation stage can set the tone for the later steps in looking at a maser flare.

Next, the Maser Database ("MaserDB", https://maserdb.net; Ladeyschikov *et al.* 2019) is consulted. This fantastic web search tool catalogs historical records of observational results, both detections and non-detections, of maser observations across a variety of maser transitions. The database can be queried using coordinates, names, in addition to offering filtering tools. In the case of M2O operations, the MaserDB can quickly provide context on the typical flux of a flaring maser in historical data, in addition to serving information on which other maser transitions have or have not been detected in the same target. For example, a 6.7 GHz methanol maser flare target may be revealed by the MaserDB to also have hydroxyl and water masers. Including these transitions in follow-up imaging by requesting multi-band observations can provide additional context such as the locations of shocks and jets in the region, which in turn help to interpret the flaring 6.7 GHz data. Good examples of this can be seen in the cases of G25.65+1.05 (Bayandina *et al.* 2019, 2023), G358.93−0.03 (Bayandina *et al.* 2022a,b) and G24.33+0.14 (Kobak *et al.* 2023).

Providing that the maser flare and progenitor seem interesting at the aforementioned stages then interest will likely lead to direct observations with more radio observatories of some common maser transitions, in addition to initiating high-cadence monitoring of flaring transitions. The participation of multiple observatories at this stage provides maser spectrum acquisition for a large number of maser transitions owing to the varieties of receivers equipped at each radio observatory. In addition, flaring behavior can be independently confirmed at this stage.

2.4. *Follow-up observations*

When a monitoring observatory identifies and reports a new maser flare, the decision whether or not to pursue follow-up observations, and if so, which, and what amount of resources to allocate, is made on a case-by-case basis. A crude visualisation of the allotment of VLBI follow-up resources can be seen in Figure 2, *right*. Generally most events deemed worth following up with VLBI are given three observation epochs in order to provide proper motion measurements of masers, in addition to spatially and spectrally isolating flaring features and identifying any maser emitting regions that are created/destroyed during the observing campaign. This information greatly helps in interpreting the structures and motions which are generating the maser emission.

Generally, the 6.7 GHz methanol maser flares are the most highly prised by the community since they are rarer and potentially indicate that a high-mass protostellar accretion burst is occurring (Fujisawa *et al.* 2015; Brogan *et al.* 2018; Moscadelli *et al.* 2017; Szymczak *et al.* 2018; MacLeod *et al.* 2018b, 2019). As previously mentioned, if a target exhibiting a flare in the 6.7 GHz methanol maser also exhibits other maser transitions, these other transitions are also included in follow-up observations to provide context at similar angular resolutions.

Comparatively, fewer of the 22 GHz water maser flares are followed up. This is mainly to retain observational resources which may need to be allocated to following up 6.7 GHz methanol maser flares, i.e. interest in following up water maser flares suffers from the basic principle of supply-and-demand.

In the case that a large scale follow-up campaign is to be initiated, the timing will depend on the precision of the knowledge of the maser's coordinates. Initiating high-resolution VLBI observations at the wrong coordinates can lead to potentially wrecked observations and time wasted. If previous VLBI-derived coordinates are known (these will be checked in the MaserDB) then this problem is avoided. In cases where precise coordinates are not available the VLA is an excellent instrument for constraining the maser location thanks to its large field of view, sub-arcsecond resolution, and ability to observe at several frequency bands in the same observing session (Bayandina *et al.* 2022a,b). The VLA is also less susceptible than VLBI to fatally resolving out too much of the maser emission at super milliarcsecond scales.

2.5. *Follow-up resources*

In order to obtain these observational follow-up data sets and respond quickly to new reports of maser flares, the M2O maintains triggerable target of opportunity (ToO) proposals at a number of facilities. By doing so, such pre-graded proposals can be activated once a trigger condition is met. Our trigger conditions relate to brightness increases of maser transitions.

We endeavor to maintain triggerable ToO proposals on all major VLBI arrays, in addition to shorter baseline interferometers such as the VLA, SMA and ALMA. Our observational resources in the infrared domain has included triggerable proposals on the JWST, Subaru and an ongoing partnership with the JCMT Transients team. Their project pursues long-term, regular infrared monitoring of 14 star forming regions, ten of which contain M2O targets.

2.6. *Interpretation and publication*

The diverse membership of observers, star formation researchers, data reducers and maser theorists, all share access to data, results, and a communications platform where interpretations can be presented and discussed. These discussions guide the path to conclusions about the observed phenomena in their appropriate context, either progressing ultimately toward publication of findings, or instead leading to further observations to test inconclusive hypotheses. As a rule, key members representing any monitoring station that reports a maser flare event to the M2O are subsequently included as co-authors in all publications following up the flare event. This is requested as a form of acknowledgement to maser monitoring observatories for promptly providing an essential information basis upon which all subsequent follow-up investigations are built.

At the time of the IAUS 380 symposium, and since inception at the IAUS 336 symposium, the M2O has 23 peer-reviewed journal publications which can be found listed on the M2O website at https://www.masermonitoring.com/#publications.

3. Case study: G358.93−0.03−MM1

Much of the aforementioned aspects of the M2O collaboration were exemplified in the identification and follow-up campaign of a 6.7 GHz methanol maser flare in high-mass star forming region G358.93−0.03.

Monitoring The maser source was one of the 488 targets monitored by the 32 m Hitachi radio telescope which is operated by Ibaraki University under the 'iMet' long-term monitoring campaign (Yonekura *et al.* 2016). A flare in the source was identified and promptly reported to the M2O via the group's mailing list and to the *astronomer's telegram* (Sugiyama *et al.* 2019). Flaring activity was seen in all of the existing maser features, in addition to the appearance and flaring of maser emission in previously empty regions of the spectrum (Breen *et al.* 2019; Brogan *et al.* 2019; MacLeod *et al.* 2019; Chen *et al.* 2020a,b), overall indicating sudden large-scale changes in physical conditions.

Establishing context Checking the entry for G358.93-0.03 in the MaserDB revealed that, prior to the excitement stoked by the accretion burst, not much was known about this star forming region aside from a few < 10 Jy maser detections and survey data (see https://maserdb.net/object.pl?object=G358.93-0.03.

To establish further context the target was observed with a large number of radio observatories and frequency bands, confirming flare activity at the 6.7 GHz transition and other methanol maser transitions, and other molecular species such as hydroxyl, prompting the mobilisation of a large-scale follow-up campaign.

Follow-up The extraordinary breadth of, and brightness of maser flaring was sufficient to gain the approval of observing time on a variety of astronomical facilities via requests of Target of Opportunity and Director's Discretionary Time (DDT). The findings of the initial follow-up and monitoring efforts influenced the observational approaches of subsequent follow-ups, such as by identifying new maser transitions which would later be mapped at ever increasing angular resolutions.

Observation time was acquired on the following instruments as part of the coordinated follow-up campaign: ATCA, VLA, SMA, ALMA, VERA, VLBA, EVN, KVN, LBA, AusSCOPE, GROND, SOFIA. Multiple epochs of data were acquired for many of these instruments. Beyond the countless single-dish radio telescope monitoring observations, the above facilities conducted more than 20 epochs of follow-up observations of G358.93−0.03.

Interpretation and publication Newly discovered maser transitions were being classified by single dish observatories (MacLeod *et al.* 2019) and interferometers (Chen *et al.* 2020a,b; Brogan *et al.* 2019; Breen *et al.* 2019), and having their brightness temperatures measured. With information from multiple molecular species and multiple maser transitions within species, attempts were made to interpret the physical conditions necessary to drive the observed maser line ratios. However, the methanol line ratios were exceptionally divergent from expectations from other star forming regions and model calculations (Cragg *et al.* 2005).

ALMA was able to identify eight millimeter cores in the region, (G358.93−0.03 MM1 through MM8) with G358−0.03 MM1 (Hereafter "G358−MM1") as the progenitor of the maser flare. A velocity gradient was revealed across the core. These observations also contributed 14 new maser discoveries in the millimeter regime (Brogan *et al.* 2019). Infrared observations confirmed that continuum dust emission had risen, pointing to the occurrence of an accretion burst (Stecklum *et al.* 2021). VLA observations produced the first maps of some of the new maser species discovered by single dish observatories and ATCA, while also uncovering sub-structures in the postulated protostellar disk which had given rise to the observed velocity gradient (Chen *et al.* 2020a,b; Bayandina *et al.* 2022a). VLBI observations traced rings of 6.7 GHz methanol masers at ever-increasing radii from the protostar, indicating that heat produced in the accretion process was traversing outward through the disk and igniting maser emission along its way (Burns *et al.* 2020b). These rings were later concatenated into a single image to provide sparse sampling of the disk at milliarcsecond resolution, revealing Keplerian rotation and a 4-arm spiral structure (Figure 3, Burns *et al.* 2020b).

Despite such a rich trove of discoveries, the entire data acquisition stage that produced these results was completed within a few months of the flare report arriving at M2O communications. It was the sharing of fresh results that provided essential context and valuable guidance which enabled subsequent discoveries to be made. Unrestricted collaboration lead to the most detailed observational account of a high-mass protostellar accretion burst to date.

To date, 11 peer-reviewed journal works have been published on the G358−MM1 flare by the M2O team, all of which crediting key members from the Ibaraki University maser monitoring programme who first provided the maser flare alert (Sugiyama *et al.* 2019). The flow of operations outlined in these proceedings, which generally describe the investigative process, for G358−MM1 and other targets, is visually summarised in Figure 4.

4. Latest developments

4.1. *The VIRAC single baseline interferometer*

In addition to cooperating with already established maser monitoring observatories and follow-up observation facilities, recent efforts have also been invested into observatory

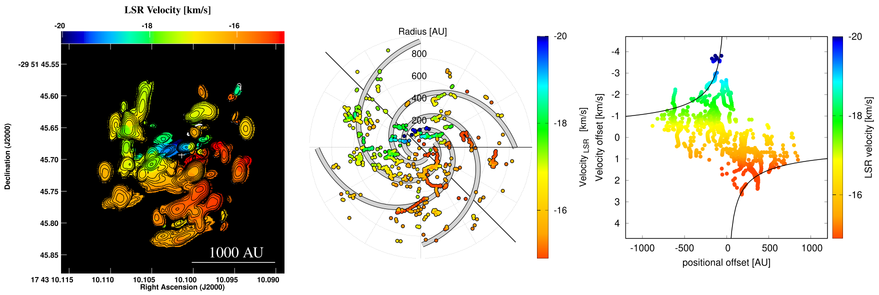
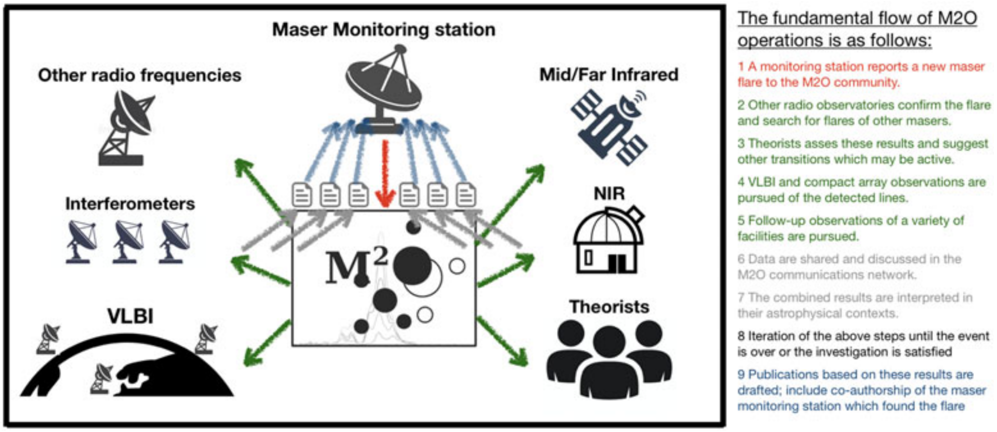


Figure 3. Figure reproduced from Burns *et al.* (2023); *Left*: Zeroth (contours) and first (colours) moment maps of the 6.7 GHz methanol maser emission in G358−MM1 which was created by combining VLBI maps. The white cross indicates the position of the G358−MM1 millimeter core (Brogan *et al.* 2019). *Middle*: Spotmap of the VLBI data sets centered on the G358−MM1 position. The black line indicates the direction of largest velocity gradient to which a position-velocity cut was taken. The spiral arms identified in Burns *et al.* (2023) are plotted as thick grey lines. *Right*: Position-velocity diagram of the maser spots. A Keplerian function for a 11.5 $M_\odot$ enclosed mass is shown as a black line.



The fundamental flow of M2O operations is as follows:

1 A monitoring station reports a new maser flare to the M2O community.

2 Other radio observatories confirm the flare and search for flares of other masers.

3 Theorists asses these results and suggest other transitions which may be active.

4 VLBI and compact array observations are pursued of the detected lines.

5 Follow-up observations of a variety of facilities are pursued.

6 Data are shared and discussed in the M2O communications network.

7 The combined results are interpreted in their astrophysical contexts.

8 Iteration of the above steps until the event is over or the investigation is satisfied

9 Publications based on these results are drafted; include co-authorship of the maser monitoring station which found the flare

Figure 4. General flow of an M2O response to a new maser flare, coloured arrows match coloured text.

development. These efforts are necessary for addressing the very specific needs of some areas of research into star formation, specifically relating to cadence. Occasionally the observing configurations and cadences offered by established, open call observing facilities is not sufficient, and alternative route must be found or created.

One example is the single-baseline interferometer at the Irbene Radio Observatory. The specific need which this facility addresses can be explained as follows. After an accretion burst it is hypothesised that a portion of in-falling material is launched in the form of a jet of plasma from the central protostellar disk region. This hypothesis has been confirmed observationally in one high-mass protostar; S255IR-NIR3, in which a detectable increase of radio emission extending perpendicular to the disk was observed (Cesaroni *et al.* 2018). However, one limitation of the study was a low precision on the initiation of the continuum flux increase start time. A higher observing cadence could provide more details about the exact delay between the accretion event and jet launching. Additionally, the rate of increase in radio emission from ejected plasma may provide clues to the geometric distribution and flow rate of jet gas.

In order to monitor radio continuum emission with high sensitivity and high cadence, the Virac single-baseline interferometer in Irbene has stood out as an excellent instrument for conducting such an investigation. The interferometer comprises one of each of 32 m and 16 m radio telescopes separated by a 800 m baseline which provides sensitivity to structures of 15 arcseconds, matching the typical sizes of ultra-compact HII regions. Utilizing the telescopes in interferometric mode also achieves deepened sensitivity by resolving out much of the background sky noise. Since the interferometer can operate at C-band, simultaneous monitoring of the radio continuum and 6.7 GHz methanol maser can be conducted. Finally, since the telescopes are operated by Ventspils University (several members of which are members of the M2O too) operations of the interferometer can be conducted with a relative freedom in terms of cadence, within the other constraints from other commitments. A pilot study from this facility, conducted as part of a successful grant application to monitor ∼ 30 high-mass protostars, is described in Steinbergs *et al.* (2022).

4.2. *A 3.7m radio telescope for astronomy in Nigeria*

The M2O cooperates with the Global Emerging Radio Astronomy Foundation (GERAF; https://www.gerafoundation.com) whose aims include sourcing funding for radio astronomy projects on various scales. One such project is the construction of a 3.7 m radio telescope which will be assembled in Nsukka, Nigeria, on the grounds of the University of Nigeria. The project funding has been raised through GERAF and the M2O will assist in providing guidance on practical maser monitoring. As time-domain maser astronomy has recently found new pastures, and since many maser emitters in the Galaxy are very bright (hundreds of Jansky and more), even a modest radio observing facility can participate in leading radio astronomy activities where cadence is king.

References

Bayandina, O. S., *et al.* 2019, *ApJ*, 884, 140
Bayandina, O. S., *et al.* 2022a, *AJ*, 163, 83
Bayandina, O. S., *et al.* 2022b, *A&A*, 664, A44
Bayandina, O. S., *et al.* 2023, *A&A*, 673, A60
Brand, J., *et al.* 2007, In *Astrophysical Masers and their Environments*, IAUS242, 223
Breen, S. L., *et al.* 2019, *ApJ*, 876, L25
Brogan, C. L., *et al.* 2018, In *Astrophysical Masers: Unlocking the Mysteries of the Universe*, IAUS336, 255
Brogan, C. L., *et al.* 2019, *ApJ* (Letters), 881, L39
Burns, R. A., *et al.* 2020a, *MNRAS*, 491, 4069
Burns, R. A., *et al.* 2020b, *Nature Astronomy*, 4, 506
Burns, R. A., *et al.* 2023, *Nature Astronomy*, 7, 557
Cesaroni, R., *et al.* 2018, *A&A*, 612, A103
Chen, X., *et al.* 2020a, *ApJ* (Letters), 890, L22
Chen, X., *et al.* 2020b, *Nature Astronomy*, 4, 1170
Cragg, D. M., Sobolev, A. M. and Godfrey, P. D. 2005, *MNRAS*, 360, 533
Fujisawa, K., *et al.* 2015, *ATEL*, 8286, 1
Gaylard, M. J., Goedhart, S. and Dhlamini, D. 2002, In *Cosmic Masers: From Proto-Stars to Black Holes*, IAUS206, 127
Green, J. A. and McClure-Griffiths, N. M. 2011, *MNRAS*, 417, 2500
Hollenbach, D., Elitzur, M. and McKee, C. F. 2013, *ApJ*, 773, 70
Kobak, A., *et al.* 2023, *A&A*, 671, A135
Ladeyschikov, D. A., Bayandina, O. S. and Sobolev, A. M. 2019, *AJ*, 158, 233
MacLeod, G. C., *et al.* 2018a, *MNRAS*, 478, 1077

MacLeod, G. C., *et al.* 2018b, *MNRAS*, 478, 1077

MacLeod, G. C., *et al.* 2019, *MNRAS*, 489, 3981

Moscadelli, L., *et al.* 2017, *A&A*, 600, L8

Stecklum, B., *et al.* 2021, *A&A*, 646, A161

Steinbergs, J., *et al.* 2022, In *European VLBI Network Mini-Symposium and Users' Meeting 2021*, 33

Sugiyama, K., Saito, Y., Yonekura, Y., and Momose, M. 2019, *ATEL*, 12446

Szymczak, M., *et al.* 2018, *MNRAS*, 474, 219

Tanabe, Y., Yonekura, Y. and MacLeod, G. C. 2023, *PASJ*, 75, 351

Volvach, A. E., Volvach, L. N. and Larionov, M. G. 2020, *MNRAS*, 496, L147

Yonekura, Y., *et al.* 2016, *PASJ*, 68, 74