Introducing the Maser Monitoring Organisation (M2O)

Ross A. Burns
EACOA, NAOJ, KASI
High-mass star formation

“High-mass stars” (> 8 $M_\odot$).

- Drivers of Galactic evolution; produce heavy elements beyond Iron.
- They represent less than 1% of stellar populations and reach MS in < 150 kyr

Theory

- Necessarily high continuous accretion rates are not backed up observationally
- Disk-aided ‘episodic accretion’ bursts; between long quiescent phases
- Simulations predict that accretion bursts are extremely rare events (typically every $10^3$-$4$ yrs) with a short, transient duration (typically a few years or less)

Lacking observational evidence

- High-mass stars typically form in deeply embedded environments at large distances, making them difficult to observe at high spatial resolution.
- 3 published observationally confirmed accretion bursts in high-mass protostars

Observational tool: Masers
Methanol

Population inversion (maser) at ~ 150 K

Water

Population inversion (maser) in shocks

There exist many more molecular maser species, but these are most commonly used
Why masers?

Methanol in the disks of high-mass protostars emit maser emission at 6.7 GHz.

The brightness of this emission is highly sensitive to temperature and density.

Changes in maser flux reveal changes in the disk radiation field.

Credit: Wolfgang Steffen / Chalmers/Boy Lankhaar

The Maser Monitoring Organisation (M2O)

Prior:
- Maser monitoring programmes already existed, but were not talking to each other.
- Transient events were only reported long after their occurrence.

Launch: 2017/09/07 @IAU Symp. 336 on Masers

Participants: Australia, Canada, China, France, Italy, Japan, Korea, Latvia, Poland, Russia, South Africa, Thailand, Ukraine, USA

Initial goals of the M2O:
- Initiate communications between monitoring programs to avoid duplicating efforts
- To alert the community to transient events
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Detection of a Bright H2O Maser Burst from G25.65+1.05 at the Simeiz Radio Telescope RT-22

ATel #10728; Alexandr E. Volvach and Larisa N. Volvach (Crimean Astrophysical Observatory), Gordon MacLeod (Hartebeesthoek Radio Astronomy Observatory), Evgyeny E. Lekht and Georgij M. Rudnitskij (Sternberg Astronomical Institute, Moscow State University), Alexandr M. Toltachev (Pushchino Radio Astronomy Observatory) on 10 Sep 2017; 19:14 UT

Credential Certification: Georgij Rudnitskij (gmr@sai.msu.ru)

Subjects: Radio, Request for Observations, Transient, Young Stellar Object

Referred to by ATEL: 10757, 10788, 10842, 10853, 11042

The source of maser emission in 22.235-GHz H2O line in the star-forming region G25.65+1.05 has experienced a new rapid flare. The peak flux density of the main feature at VLSR = 42.5 km/s was: 2017 April 26 - 600 Jy (Simeiz RT-22 radio telescope); 2017 May 12 - 400 Jy (Simeiz); 2017 June 13 - 410 Jy (Simeiz); 2017 July 25 - 316 Jy (Pushchino RT-22 radio telescope); 2017 August 10 - 620 Jy (Simeiz); 2017 August 21 - 840 Jy (HartRAO); 2017 August 25 - 813 Jy (Pushchino); 2017 August 27 - from 1400 Jy to 2500 Jy (Simeiz); 2017 September 7 - 1700 Jy (Simeiz); 2017 September 8 - 20500 Jy (Simeiz); 2017 September 9 - 21000 Jy (HartRAO). As observed previously in Pushchino, the H2O maser G25.65+1.05 had a strong flare in November-December 2016, its peak flux density exceeding 40000 Jy (paper submitted to Astronomy Reports). Follow-up observations of this source are highly desirable.
The Maser Monitoring Organisation (M2O)

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VLBI observations of the G25.65+1.05 water maser superburst

This paper reports observations of a 22 GHz water maser ‘superburst’ in the G25.65+1.05 massive star-forming region, conducted in response to an alert from the Maser Monitoring Organisation (M2O). Very long baseline interferometry (VLBI) observations using the European VLBI Network (EVN) recorded a maser flux density of $1.2 \times 10^4$ Jy. The superburst was investigated in the spectral, structural, and temporal domains and its cause was determined to be an increase in maser path length generated by the superposition of multiple maser-emitting regions aligning in the line of sight to the observer. This conclusion was based on the location of the bursting maser in the context of the star-forming region, its complex structure, and its rapid onset and decay.

H2O line in the star-forming region G25.65+1.05

As observed previously in Pushchino, the H2O maser G25.65+1.05 had a strong flare in November-December 2016, its peak flux density exceeding 40000 Jy (paper submitted to Astronomy Reports). Follow-up observations of this source are highly desirable.
M2O operations

Other radio frequencies

Interferometers (ex. ALMA)

Monitoring station

Mid/Far Infrared

NIR (ex. Subaru)

VLBI

Theorists
M2O operations

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M2O operations
Maser flare: G358.93-0.03

First flare of the 6.7 GHz methanol maser reported to the M2O

K. Sugiyama alerted the M2O in mid January 2019

Hitachi 32m
Operated by Ibaraki-U

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Daily monitoring
Maser flare: G358.93-0.03

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Hitachi 32m
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http://vlbi.sci.ibaraki.ac.jp/iMet/G358.9-00-190114/
KS, Y. Yonekura, et al. (2019), ATel
Results from the M2O: Monitoring
Results from the M2O: Monitoring

Burst duration was about 4 months

After the burst the maser stayed brighter than pre-burst

Many new/rare masers were detected
Results from the M2O: ALMA
Results from the M2O: ALMA

The environment is a cluster

Identified the bursting source: MM1

Found 14 new maser transitions, this implies unusual physics and chemistry

First proof of the torsionally excited maser pumping route

Velocity coherent maser structure ~1200 AU

Results from the M2O: ALMA

The environment is a cluster

Sub-arcsecond (Sub)millimeter Imaging of the Massive Protocluster G358.93−0.03: Discovery of 14 New Methanol Maser Lines Associated with a Hot Core


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2 Department of Astronomy, University of Virginia, P.O. Box 3818, USA
3 Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA
4 Hartebeesthoek Radio Astronomy Observatory, P.O. Box 443, Krugersdorp 1740, South Africa
5 The University of Western Ontario, 1151 Richmond Street, London, ON N6A 3K7, Canada
6 SUPA, School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews KY16 9SS, UK
7 INAF-Istituto di Radioastronomia, via P. Gobetti 101, I-40129 Bologna, Italy
8 Italian ALMA Regional Centre, via P. Gobetti 101, I-40129 Bologna, Italy
9 Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, Osawa 2-21-1, Mitaka, Tokyo 181-8588, Japan
10 48
10.2 10.0 17:43:09.8
Right Ascension (J2000)

Results from the M2O: SOFIA
Results from the M2O: SOFIA

SED shows FIR enhancement

$L \sim 5000 \, \text{Lo}$

$M \sim 10 \, \text{Mo}$

**Mass accretion rate:**

However, since MM1 is likely in an earlier evolutionary stage, preceding the ZAMS, the above assumption may not hold. A different and presumably more realistic approach is possible using the stellar radius from the RT modeling of the pre-burst SED together with the stellar mass of $12 \pm 3 \, \text{M}_\odot$ derived from the kinematic model of the spiral-arm accretion flows (Chen et al. 2020b). This leads to $M_{\text{acc}} = 5.3^{+1.1}_{-4.4} \times 10^{-4} \, \text{M}_\odot$, and $\dot{M}_{\text{acc}} = 3.2^{+5.4}_{-3.0} \times 10^{-3} \, \text{M}_\odot \, \text{yr}^{-1}$. The large positive error range is mainly due to the corresponding large uncertainty of the stellar radius. To put this into perspective, during its short burst G358 MM1 consumed about 180 Earth masses. Notably, because of the small disk mass, the accreted fraction represents 16% of the total. This raises the question whether the lightweight disk is a stable or transient feature.

Stecklum et al. 2020, accepted to A&A
https://arxiv.org/abs/2101.01812
Results from the M2O:

Infrared observations of the flaring maser source G358.93–0.03*

SOFIA confirms an accretion burst from a massive young stellar object

B. Stecklum¹, V. Wolf¹, H. Linz², A. Caratti o Garatti³, S. Schmidl¹, S. Klose¹, J. Eislöffel¹, Ch. Fischer⁴, C. Brogan⁵, R. Burns⁶, O. Bayandina⁶, C. Cyganowski⁹, M. Gurwell¹⁰, T. Hunter⁴, N. Hirano¹¹, K.-T. Kim¹², G. MacLeod¹³, K. M. Menten¹⁴, M. Olech¹⁵, G. Orosz¹⁶, A. Sobolev¹⁷, T. K. Sridharan¹⁰, G. Surcis¹⁸, K. Sugiyama⁶, J. van der Walt¹⁹, A. Volvach²⁰, and Y. Yonekura²¹

(Affiliations can be found after the references)

Received October 11, 2020; accepted December 21, 2020

Stecklum et al. 2020, accepted to A&A
https://arxiv.org/abs/2101.01812

This leads to $M_{\text{acc}} = 5.3 \pm 1.1 \times 10^{-4} M_\odot$, and $M_{\text{acc}} = 3.2 \pm 0.4 \times 10^{-3} M_\odot \text{yr}^{-1}$. The large positive error range is mainly due to the corresponding large uncertainty of the stellar radius. To put this into perspective, during its short burst G358 MM1 consumed about 180 Earth masses. Notably, because of the small disk mass, the accreted fraction represents 16% of the total. This raises the question whether the lightweight disk is a stable or transient feature.
Results from the M2O: VLBI (LBA)
VLBI images of methanol masers during an accretion burst

G358-MM1
High-mass protostar which underwent an accretion burst in 2019

Beamsize: 10 x 3 mas

Contours: MOM0 (flux density)

Colours: MOM1 (Velocity [km/s])

White cross: ALMA mm core
Results from the M2O: VLBI (LBA)

- Implies a translocation of 1-2 mas/day, which is 11,700 to 23,400 km/s at the source's kinematic distance of 6.75 kpc (equivalent to 0.04 to 0.08c).

- Methanol masers die at v >10 km/s i.e. Too fast to be proper motion.

Burns et al., 2020, Nature Astronomy, vol 4, 506
Results from the M2O: VLBI (LBA)

- Compact (260 au @ 6.75 kpc)
- Ring-like
- Center on MM1 (Brogan+ 19)

Interpretation

Temperatures: 150-200 K
Radius: 150-200 K

Burns et al., 2020, Nature Astronomy, vol 4, 506
Results from the M2O: VLBI (LBA)

- Compact (260 au @ 6.75 kpc)
- Ring-like
- Center on MM1 (Brogan+ 19)

Masers trace a “heat-wave” of accretion energy propagating outward.

Burns et al., 2020, Nature Astronomy, vol 4, 506
Results from the M2O:
VLBI (Combined)

LBA, EVN, VLBA
Results from the M2O: VLBI (Combined)
Results from the M2O:
VLBI (Combined)

Eventually the ring of masers disappeared
Results from the M2O: VLBI (Combined)

371 AU

697 AU

720 AU

884 AU

918 AU

869 AU
Results from the M2O: VLBI (Combined)

The expansion slowed down after ~700 AU

This is about the radius of the snow line for methanol
Results from the M2O: VLBI (Combined)
Results from the M2O: VLBI (Combined)

We can see the suggestion of spiral arms or accretion flows in the combined image.

The combined PV diagram shows the signature of an inflating Keplerian disk.

The dynamic mass is estimated to be 1.6 Mo, however we know the true mass is ~10 Mo from SED analyses, this means the system is face-on.

The combined M2O data set gives the most detailed picture of an accretion burst in a high-mass protostar.
What we learned from the G358 maser flare

Regarding high-mass star formation
- Strongest evidence yet for episodic accretion in high mass star formation
- Accretion events show variety (S255-IR, NGC6334, G358)
- Accretion events give rise to exotic maser emission (need new models)
- Disks show structure / clumsiness, consistent with epi. acc. theory

Regarding M2O operations
- The 6.7 GHz methanol maser readily identifies accretion events
- Is also easy to monitor with radio telescopes
- Our operations model for flare alerts and collaborations works
- Multi-wavelength and multi-epoch follow-up observations needed
- Collaboration (Radio, mm, NIR, MIR, FIR, etc.)

Triggerable Target of Opportunity proposals are necessary to catch bursts
Activities after the G358 maser flare

Expanded observing resources

More radio telescopes monitoring

More partners specialising in a wide range of facilities

Triggerable ToO proposals:
- EVN
- KaVA
- LBA
- VLBA
- Subaru

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<td>19/19/19</td>
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Activities after the G358 maser flare

More members
(Currently 71)

More publications
(Currently 16 published or accepted)

More maser flares

- M2O targets:

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<td>G359.617-0.251</td>
<td>6.7</td>
<td>120</td>
<td>200</td>
<td>150</td>
<td>Yonekura</td>
<td>Ib, Hh,</td>
<td>decreasing</td>
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<td>95</td>
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<td>236</td>
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<td>-</td>
<td>30k</td>
<td>-</td>
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<td>7k</td>
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<td>120</td>
<td>Ladeyschikov</td>
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</table>

(Ib = Ibaraki) (Tr = Torun) (Sz = Simeiz) (Hh = HartRAO) (Ef = Effelsberg) (Ky = KVN Yonsei) (Vs = Ventspil) (Vr = VERA stations) (Mc = Medicina) (Ps = Puschino) (Oa = OAO-WFC)
Our interests are not restricted to high-mass star formation.

We are always looking for more ways to collaborate and use transient maser emission as tracers for astrophysical processes.

Thank you for listening.