Episodic accretion in high-mass star formation: Maser flares as indicators and their follow-up

The Maser Monitoring Organisation (M²O)

Masers as Canary Birds!

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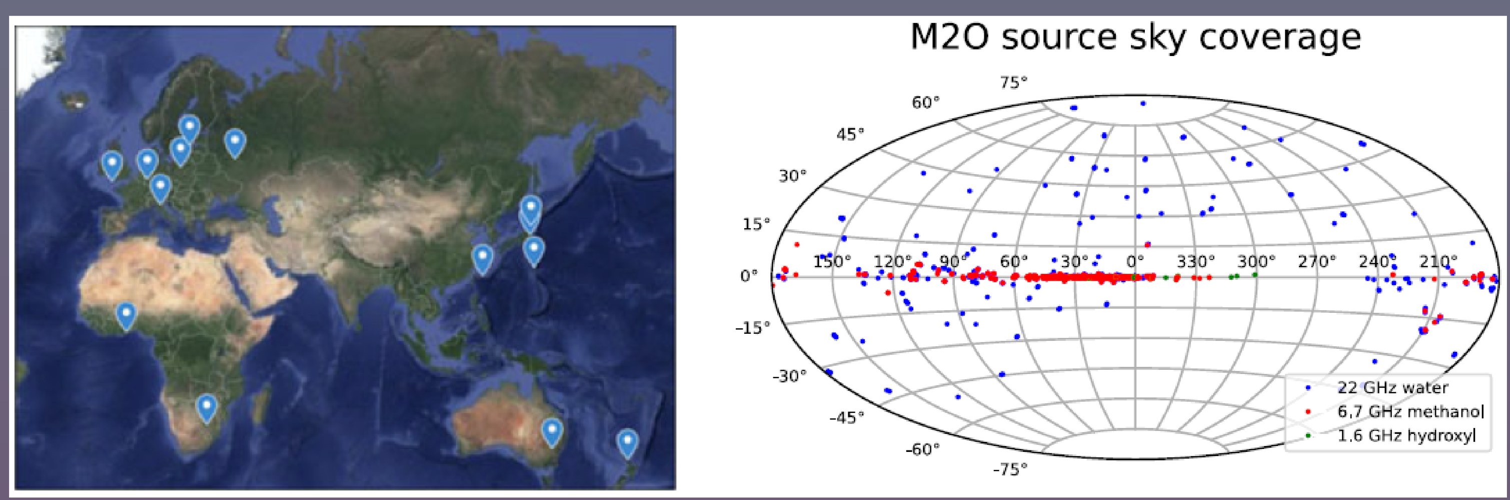
Episodic accretion whereby the accretion rates increase drastically for a short period of time (on the order of months to years) may constitute an important mode for the build-up of a protostar's mass. Most of the promptly released accretion luminosity would be re-processed and eventually released as far-infrared (FIR) radiation (30-300 µm). But no FIR sky monitoring is in place to catch such rare events. Methanol class II masers can be used as tracers of such processes since they directly react to the FIR radiation field, and maser flares will herald the accretion event. The Maser Monitoring Organisation (M2O) is an initiative to coordinate both the monitoring of a large number of maser sites, and to organise swift multi-wavelength high-resolution follow-up observations to enlighten the physical and chemical processes involved in these exciting events.

Single-dish maser monitoring with 30-m class telescopes all over the world

Within M2O, 14 single-dish stations in Europe, East Asia, Australia and Africa do monitoring. See Burns, R. 2024, IAUS 380, 443



562 6.7 GHz Methanol maser sites
260 22 GHz water maser sites
65 L-band OH maser sites

Monitoring at different cadences (weekly to several months).

Current working group coordinator is *Fanie van den Heever*.

Flare statistics over the previous 7 years (start of the M2O in 2017): 1.5 – 2.0 strong flares per year per maser flavour (CH_3OH, H_2O).

Multi-wavelength follow-up from the Infrared to the (sub-)millimeter

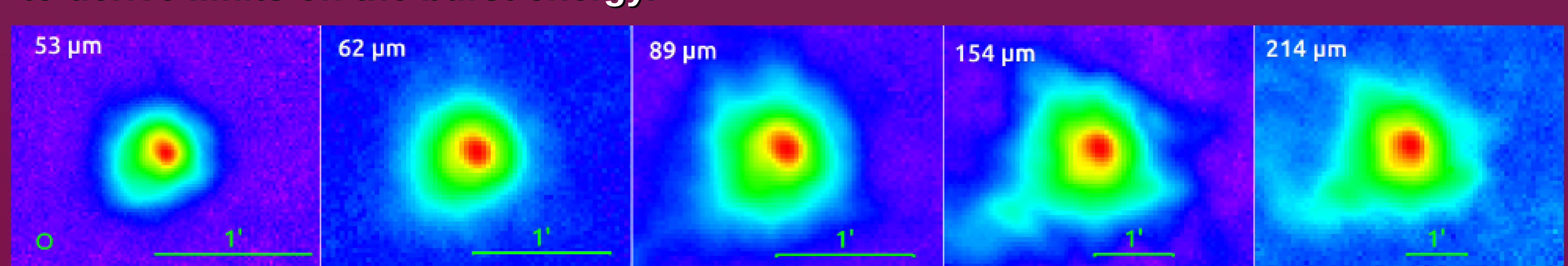
- → Access to thermal dust emission
- → (sub-)millimeter sensitive to temperature and dust opacity changes
- → Far-IR sensitive to luminosity changes, most energy is released there!
- → Mid-IR with many solid-state feature diagnostics (silicates, ices)
- → Near-IR multi-epoch imagery: light echoes → envelope structure

An SMA Target-of-Opportunity program and ALMA DDT proposals have gained many insights into previous big bursts (PIs: *Todd Hunter & Crystal Brogan*).
A JWST ToO program has been triggered in summer 2023, first results are under discussion (PI: *Alessio Caratti o Garatti*).

Lament I: With the demise of SOFIA, no readily available facility exists that can probe the important far-infrared range!

Lament II: The NEOWISE IR sky survey at 3.4 + 4.6 µm will end in 2024!

Example: An archival find in the high-mass star-forming region G323.46-0.08!
Historic maser monitoring (pre-M2O) had revealed a strong maser burst in that clump between 2013-2015 (see also Proven-Adzri et al. 2019, MNRAS 487, 2407).
We consulted the NEOWISE data base and could recover the event also as a brightness burst and following slow decay in the infrared around that time.
Our SOFIA/HAWC+ observations from 53 to 214 µm, performed in 2022, two years after the end of the burst, constrained the strength of the thermal afterglow and were crucial to derive limits on the burst energy.



Object	M_* [$M_\odot$]	L_{pre} [10^3 $L_\odot$]	L_{peak} [L_{pre}]	ΔL [10^3 $L_\odot$]	t_{rise} [yr]	Δt [yr]	$\dot{M}_{acc}$ [10^{-3} $M_\odot$ yr^{-1}]	E_{acc} [10^{45} erg]	M_{acc} [M_{Jup}]
G323.46-0.08 (G323)*	23	60	5.4	260	1.4	8.4	0.8	90	7
S255IR NIRS3*	20	30	5.5	130	0.4	2.5	5	12	2
G358.93-0.03-MM1*	12	5.0	4.8	19	0.14	0.5	1.8	2.8	0.5
NGC 6334I MM1*	6.7	3	16	44	0.6	>8	2.3	>40	>0.4
V723 Car	10?	~ 4			4	~ 15			
M17 MIR	5.4	1.4	6.4	7.6		9-20	~ 2		

Outburst parameters for massive YSOs with a well-characterised episodic accretion event so far (from Wolf et al. 2024).

See: Wolf, V., Stecklum, B. et al. 2024, A&A accepted, arXiv:2405.10427

Maser follow-up with the JVLA

- → Resolve maser distribution with (sub-) arcsecond resolution
- → Maser kinematics, differentiating different (radial) velocity component
- → Comparison of the distribution and (co-)location of different maser species
- → Access to centimeter continuum with (sub-) arcsecond resolution

A renewed Target-of-Opportunity program is in place and can be triggered for multi-epoch follow-up. PI is *Olga Bayandina.*

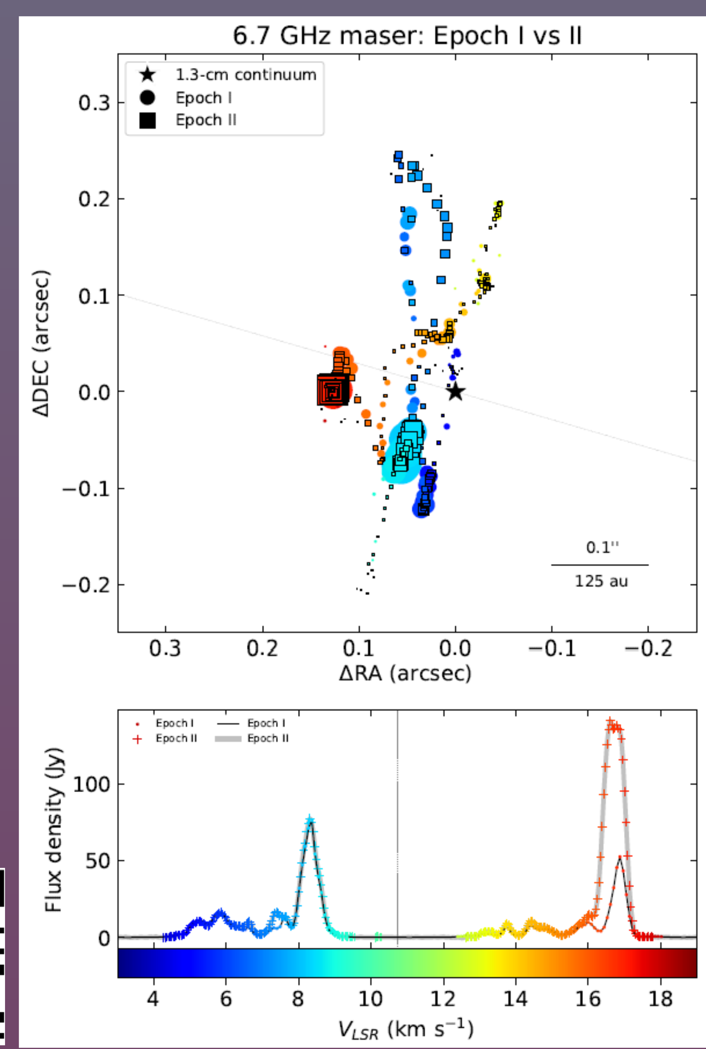
Example: Two epochs of JVLA maser observations for the high-mass star-forming region G11.497-1.485 (d ~1.25 kpc).

Shown is the result for the 6.7 GHz CH_3OH masers.

Epoch I : April 6, 2023 some maser components had risen already by a factor of 4 compared to the longterm average
Epoch II: July 18, 2023 shortly after the peak flare that amplified one velocity component by a factor of >10

Redistribution of flux between these two epochs: Flux maximum shifted from 8-9 km/s to 16-17 km/s, peaking at a different location.
Has a heatwave from an accretion event emanating from the cm continuum source reached different velocity component maser spots at different times?

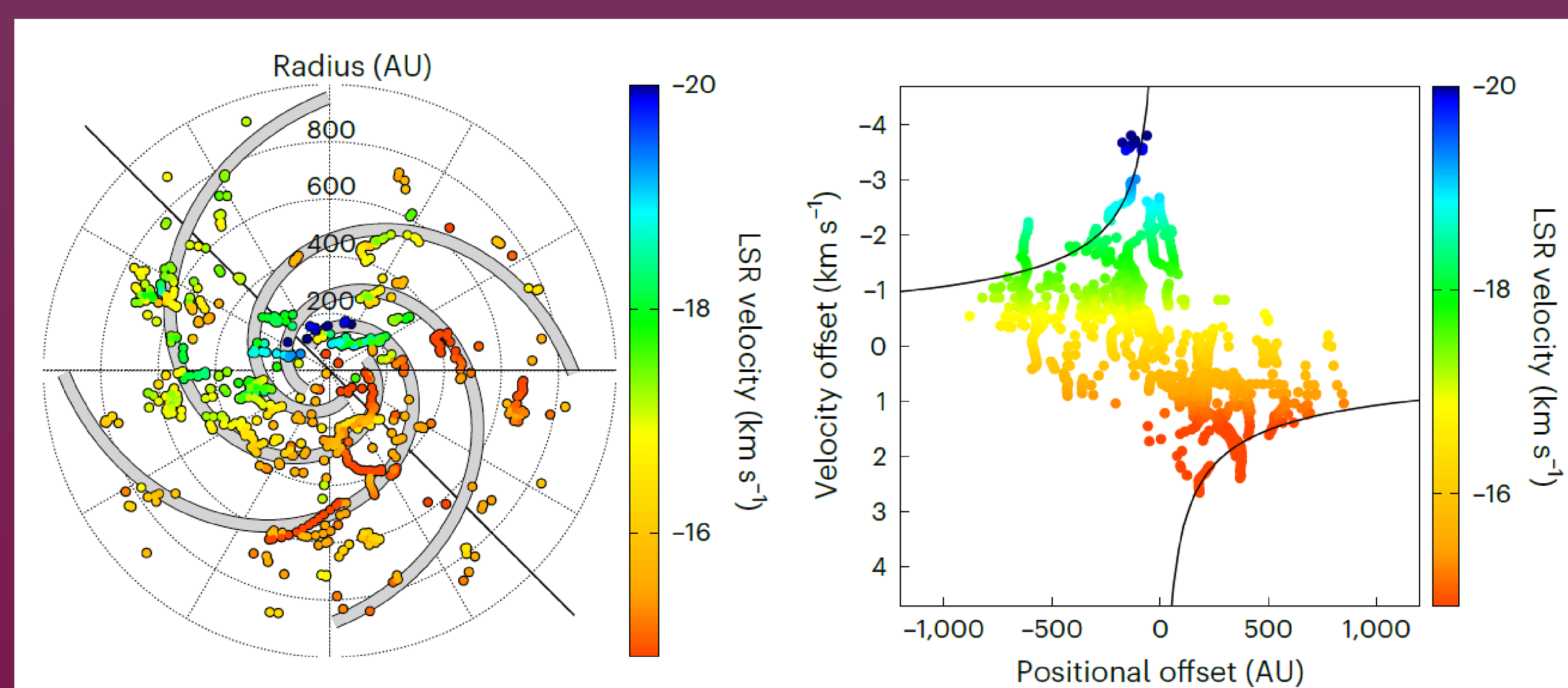
See: Bayandina, O. et al. 2024, A&A 684, A86



High-resolution VLBI studies

- → Needs strong compact masers!
- → Resolve maser distribution and kinematics with milli-arcsecond resolution
- → Zoom in to identify sub-structures on circumstellar disk scales at several kilo-parsec distances

Several Target-of-Opportunity and DDT programs can be used on different facilities (VLBA, LBA, EVN) for multi-epoch follow-up. PI is *Ross Burns*.



Example: Six VLBI epochs of 6.7 GHz maser observations for the high-mass star-forming region G358.93-0.03 (d~6.75 kpc), combined in one plot. By analysing the first three epochs, the existence of a heatwave travelling outwards with 0.15 c was already identified in Burns et al. 2020, Nature Astronomy 4, 506.
Left: Spotmap of the VLBI data sets centered on the G358 ALMA position. The spatial and spectral pattern is consistent with a four-arm spiral, plotted as thick grey lines. The black line indicates the direction of largest velocity gradient to which a position-velocity cut was taken.
Right : Position-velocity diagram of the maser spots along this p-v cut. A Keplerian function for a 11.5 M_{sun} enclosed mass is shown as black curves.

See: Burns, R. et al. 2023, Nature Astronomy 7, 557