Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Masers in accretion burst sources

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Abstract. Recently, remarkable progress has been made in understanding the formation of high mass stars. Observations provided direct evidence that massive young stellar objects (MYSOs), analogously to low-mass ones, form via disk-mediated accretion accompanied by episodic accretion bursts, possibly caused by disk fragmentation. In the case of MYSOs, the mechanism theoretically provides a means to overcome radiation pressure, but in practice it is poorly studied - only three accretion bursts in MYSOs have been caught in action to date. A significant contribution to the development of the theory has been made with the study of masers, which have proven to be a powerful tool for locating "bursting" MYSOs. This overview focuses on the exceptional role that masers play in the search and study of accretion bursts in massive protostars.

Keywords. Stars: formation, Masers

1. Introduction

Massive stars play a critical role in, both physical and chemical, formation of galaxies (e.g. Greif 2015). However, the question of how massive stars themselves form remains debatable.

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It seems reasonable to assume that massive young stellar objects (MYSOs) should follow the same mechanisms that we see in low-mass protostars, and thus the formation of massive stars should be a scaled-up version of low-mass star formation. Nevertheless, as a protostar accumulates mass, it also emits more and more energy. At some point, the growing radiation of the protostar inevitably begins to push away the surrounding matter, thus cutting itself off from the mass supply (e.g. Hosokawa *et al.* 2012). The situation only worsens if radiation pressure is trapped in a dense gas and dust shell. And this applies to massive protostars, which evolve much faster than low-mass stars and remain deeply embedded in their parental envelopes throughout the early stages of the evolution (e.g. Zinnecker & Yorke 2007).

Although radiation pressure plays an important role in the formation of MYSOs, it can fatally stop the accumulation of mass only under the assumption that stellar evolution is laminar and continuous. In reality, nature has come up with a few ways to get around the issue. Instead of pushing matter uniformly in all directions, the radiation pressure finds an outlet in certain, physically favorable directions, thus forming collimated flows without destroying the accretion of matter onto a star (Moscadelli *et al.* 2020). Another critical point is the fact that the rate of accretion onto a protostar is not constant, but episodic, with episodes of rapid accretion (bursts). The prevailing idea at the moment is that MYSOs form via disk-mediated accretion, accompanied by episodic accretion bursts, possibly caused by disk fragmentation (e.g. Meyer *et al.* 2019).

The problem is that, despite the general theoretical understanding of the process, we struggle to gather a statistically significant sample of massive protostars going through these critical burst accretion episodes. When we discover a new object or event, the question arises whether that thing is so unique that we have never been lucky enough to catch it in action before, or whether our observation methods and samples were missing the point. The way to test these two possibilities is to conduct extensive observations. A good example of this approach are fast radio bursts (FRBs), which have gone from the first discovery in 2007 to hundreds of events detected to date (CHIME/FRB Collaboration *et al.* 2021). Massive stars per se are a challenging observational target. They are rare and located at far distances (e.g. Zinnecker & Yorke 2007), making any statistical or high-resolution study taxing. As mentioned above, massive stars evolve rapidly, remaining hidden in the natal clouds for most of their evolution. Dense envelopes obscure MYSOs from direct observations, leaving only the window of sub-millimeter, IR, and radio wavelengths open. Additionally, the rapid evolution means that any particular evolutionary stages are short and demand quick-response facilities and observational techniques. Models suggest that accretion bursts constitute only $\sim$1.7% of the formative first 60 kyr of massive stars (Meyer *et al.* 2019). No accretion burst in MYSO were found up until 2016, when the first such event was discovered in IR observations (Caratti o Garatti *et al.* 2017). Since then, only two more accretion bursts have been detected "in action", e.g. during the burst epoch (Hunter *et al.* 2017; Stecklum *et al.* 2021), but this is a promising start, because these detections were made possible by a change in the observational strategy.

Accretion bursts traced by continuum emission require "pre-burst" data and confirmation via multi-epoch observations with mm-interferometers such as ALMA, NOEMA, or the SMA - thus limiting the target sample to well-studied MYSOs. Moreover, to our knowledge, there is no monitoring program for (sub-)mm continuum emission with a cadence that would detect bursting sources during a burst onset. A turning point in the search for accretion bursts occurred when it was noticed that large accretion events in MYSO are accompanied by maser flares (e.g. Hunter *et al.* 2017; Szymczak *et al.* 2018b; MacLeod *et al.* 2018). Bright and compact, masers trace physical conditions and dynamics of the environment around MYSOs, yet are easily accessible to observation using a variety of instruments, from single-dish telescopes (e.g. Szymczak *et al.* 2018a) to space-VLBI (e.g. Sobolev *et al.* 2018). In contrast to continuum sources, pre-burst data are available for most maser sources thanks to maser surveys conducted using single-dish telescopes and interferometers (see Maserdb, the database of astrophysical masers, Ladeyschikov et al. 2019).

Masers are numerous, providing a rich selection of possible targets, but also fragile, being finely tuned to local physical conditions (e.g. Ellingsen *et al.* 2007 and Breen *et al.* 2019a). Changes in temperature, density, or velocity field of masering region can result in brightening (flare) or fading of maser emission. Spatial distribution of masers can reveal the temperature, density, and radiation enhancements in the region, while the kinematics of the maser spots can indicate gas motions. Hence the study of maser emission can provide us with the record of the evolution of a particular star, with maser flares highlighting accretion bursts, as no other tracer can.

2. Sample of the known accretion burst sources

To date only three definite accretion bursts, observed during the accretion events and confirmed both in IR and maser observations, have been found: S255IR (Caratti o Garatti *et al.* 2017), NGC6334I (Hunter *et al.* 2017), and G358.93-0.03 (Stecklum *et al.* 2021). The first two sources, S255IR and NGC6334I, exercised accretion bursts in 2015 (Caratti o Garatti *et al.* 2017; Hunter *et al.* 2017) and set the scene for the follow-up search of the sources of this kind. The discovery of the burst in the latest source, G358.93-0.03, happened in 2019 (Stecklum *et al.* 2021) and was the product of such a dedicated quest.

In all three mentioned cases of accretion bursts, outstanding change in flux density and structure of sub-millimeter, IR, and radio emission from the sources has been noted (Caratti o Garatti *et al.* 2017; Hunter *et al.* 2017; Stecklum *et al.* 2021). IR-brightening of the central source is one of the defining features of accretion bursts in massive star formation, however even such a small sample of the sources showed a surprising variety of the IR emission parameters, with G358.93-0.03 being the first NIR- and (sub)mm-dark but FIR-loud accretion burst (citealpStecklum2021).

According to the analysis of archival data, in addition to the core sample, at least three more sources are thought to experience accretion bursts. The source M17 MIR showed correlated variations in MIR and 22 GHz water maser fluxes, indicating two accretion bursts separated by a six years long quiescent phase (Chen *et al.* 2021). The object is extremely young, and minor accretion bursts are expected to be frequent in the very early stages of massive star formation (e.g. Meyer *et al.* 2019). An accretion burst in another source, V723 Car, was suspected on basis of NIR images analysis, but since the burst was found post factum, no information on the accretion luminosity is available (Tapia *et al.* 2015). This source also has no associated masers. In contrast, G323.46-0.08 is thought to go through an accretion burst solely based on 6.7 GHz maser data without IR confirmation (Proven-Adzri *et al.* 2019). The periodic 6.7 GHz methanol maser in the source showed a flare and appearance of new maser features (Proven-Adzri *et al.* 2019).

A few more sources showed features that can potentially be interpreted as signs of accretion bursts and be added to the sample. Of particular interest are sources housing periodic masers, such as G351.78-0.54 (MacLeod, G. C. & Gaylard, M. J. 1996), G107.298+5.639 (Stecklum *et al.* 2018; Olechi *et al.* 2020) and G323.46-0.08 (Proven-Adzri *et al.* 2019). The periodic behaviour of the maser emission makes them attractive targets for long-term monitoring and provides a record of accretion instabilities in the sources.

3. Masers tracing accretion bursts

Despite the fact that the sample of accretion burst sources in MYSO is very limited, methanol masers at 6.7 GHz have already shown to be the best indicator of events of this type (e.g. the 6.7 GHz maser flare reported in Fujisawa *et al.* (2015) triggered the IR observations of S255IR NIRS3). The abundance of such masers provides a large sample of target sources (e.g. Yang *et al.* 2019). Remarkably, 6.7 GHz methanol masers are known to be associated exclusively with high-mass protostars (Minier *et al.* 2003). The low frequency and usually high fluxes allow monitoring even using single-dish telescopes with a small and imperfect active surface. Methanol masers at 6.7 GHz show consistent spectra with stable or periodic fluxes, thus any sudden change can be identified in monitoring data (e.g. Szymczak *et al.* 2018a).

However, the 6.7 GHz transition is just one example of the many radiatively pumped class II methanol masers that arise during accretion bursts. Due to the increase in incident photons during accretion bursts, masers in the vicinity of a bursting source exhibit an increased flux. This gives rise to a very specific type of maser flare - class II methanol masers show extraordinary fluxes with appearance of new spectral features (e.g. Fujisawa *et al.* 2015; Sugiyama *et al.* 2019). During the latest discovered accretion event in G358.93−0.03, multiple maser transitions flared, and rare, previously undiscovered maser species and transitions were found to arise (e.g. Breen *et al.* 2019a). The energy of the accretion burst ignited previously undetected class II methanol masers, including the first ever discovered torsionally excited methanol masers (Breen *et al.* 2019a; Brogan *et al.* 2019; MacLeod *et al.* 2019). More than 30 maser lines were detected in a wide range of frequencies from 6.18 GHz to 361.2 GHz.

Simultaneous VLA observations of several different methanol masers detected in G358.93−0.03 during the burst showed that they all trace the same region around the central protostar (Bayandina *et al.* 2022a). However, the distribution of the methanol masers changed drastically from the burst epoch to post-burst epoch (Bayandina *et al.* 2022a; Burns *et al.* 2020b). A similar profound change in the location of the 6.7 GHz maser emission within the source was found in S255 after the burst (Moscadelli *et al.* 2017). And in the case of NGC6334I, a strong 6.7 GHz methanol masers was detected towards the bursting source MM1 at the burst epochs, while no masers had ever been seen towards it before (Hunter *et al.* 2018). Another common feature of flaring 6.7 GHz maser emission in all the burst sources is the presence of an extended component of methanol emission which is largely resolved with VLBI arrays but can be studied with compact arrays (Moscadelli *et al.* 2017; Hunter *et al.* 2018; Burns *et al.* 2020b).

The extreme energy of accretion bursts allows us to study fine structure of accretion disks with the help of methanol maser emission. The VLA images obtained for G358.93−0.03 during the flare hinted at the presence of spiral arm structures within the accretion disk but the low resolution of the compact array data limited the extent of the interpretation (Bayandina *et al.* 2022a). The theory was confirmed in the multi-epoch VLBI observations of the 6.7 GHz maser in G358.93−0.03 presented in Burns *et al.* (2023). In a series of VLBI observations, the thermal radiation ("heatwave") from the accretion burst was caught propagating with subluminal velocities outwards from the central accreting high-mass protostar to the outer radii of the accretion disk (Burns *et al.* 2023). Combining together the images of the heatwave propagation and fitting the resulting map, Burns *et al.* (2023) were able to infiltrate a four-arm spiral structure in the Keplerian disk around the bursting source in G358.93−0.03.

Apart from methanol masers, some other masers species in vicinity of the bursting sources have been detected. Notably, the newly discovered molecular maser species of HDO, HNCO, and $^{13}CH_3OH$ detected with the VLA were discovered to trace spiral-arm accretion flows in G358.93−0.03 (Chen *et al.* 2020a,b). The 6.7 GHz methanol maser flare in NGC6334I MM1 was accompanied by increased flux density of OH masers not only at 1665 MHz but also at 4660 and 6031 MHz (MacLeod *et al.* 2018). Accretion burst sources therefore appear to be the most promising laboratories for future discoveries of new maser species.

Accretion bursts and methanol maser flares are typically followed by an H_2O maser flare (Brogan *et al.* 2018; Hirota *et al.* 2021; Bayandina *et al.* 2022b) triggered by the light from the burst scattered by the dust in the outflow cavities (the so-called "light echo") (Caratti o Garatti *et al.* 2017). For example, the VLA images of the 22 GHz water maser emission in G358.93−0.03 showed a significant change in both the morphology and velocity gradient of the maser associated with the bursting source MM1. In addition, a bigger region seems to be affected by the accretion event as the emission of the water masers associated with other point sources in the region appeared to be suppressed at the post-burst epoch (Bayandina *et al.* 2022a).

4. Maser Monitoring Organisation

Discussion of the role of maser in the study and search of accretion bursts is inadequate without mentioning the activities of Maser Monitoring Organisation (M2O) (Burns *et al.* 2022). In order to utilise the potential of maser flares as indicators of accretion bursts, maser monitoring programs from all around the globe came together in 2017 (soon after the first accretion burst discovery) and created the M2O. M2O is a global cooperation of maser monitoring programs that searches for maser flares and manages their follow-up interferometric studies. In the few first years of the M2O, dozens of maser flares were discovered and even though not all of them were associated with accretion bursts, each flare provided valuable insights into the accretion/ejection process in MYSO (see the publication list on the project website).

The most significant achievement of the Maser Monitoring Organisation to date is the organisation and management of the follow-up observations of G358.93−0.03 after the 6.7 GHz methanol maser flare. The coordinated actions of the various scientific groups within the organisation (i.e. single-dish monitoring; IR, compact array, and VLBI follow-up; theoretical modelling) allowed for the most comprehensive and diverse observations of the accretion disk produced so far (Breen *et al.* 2019a; Brogan *et al.* 2019; MacLeod *et al.* 2019; Burns *et al.* 2020a; Chen *et al.* 2020a,b; Volvach *et al.* 2020; Stecklum *et al.* 2021; Bayandina *et al.* 2022a,b; Burns *et al.* 2023). It should also be noted that such a large variety of data was obtained thanks to extensive preparatory work, in anticipation of the discovery of such a transitive event, the M2O has obtained triggered and ToO observing time with a number of the most significant astronomical facilities. The successful study of the accretion burst in G358.93−0.03 inspires hope that the next accretion event in MYSO will get even more coverage and disclose many more secrets of the early stages of massive star formation.

5. Perspectives

The termination of the Stratospheric Observatory for Infrared Astronomy (SOFIA) mission presented a major setback for the study of accretion bursts in MYSO. The telescope provided critical confirmation of accretion bursts in the IR range (e.g. citealp-Caratti2017) which no ground-based telescope can access. The loss of the SOFIA telescope is supposed to be compensated by the activities of the James Webb Space Telescope (JWST), however, at the moment, the demand for the instrument's observing time is too great and such short-lived transient events as accretion bursts would most

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likely be missed. Although this is not an optimal solution, we still can use NIR spectral imaging to study NIR-bright accretion bursts (such as S255IR NIRS3 or G323.46-0.0) and sub-mm/mm data to study the NIR dark ones (such as G358.93-0.03 or NGC6334I) to confirm the burst and recover some physical characteristics.

Considering the degradation of the IR research, masers have taken on even greater importance. The activities of the M2O showed the importance of maser monitoring with single-dish telescopes. The accretion burst cases detected so far showed a wide variety of flaring masers at different frequencies. In this context, upgrading of single-dish telescopes and VLBI arrays with new high-frequency receivers can open up new perspectives for the research. For example, the INAF radio telescopes (64-m Sardinia, 32-m Medicina and 32-m Noto Radio Telescopes, Italy) are planned to be equipped with the new high-frequency receivers simultaneously operating in K, Q, and W frequency bands (central frequencies: 22, 42, and 100 GHz) by the end of 2023 (Bolli et al. in print). Note that many of the extremely rare, never-before-detected methanol masers found in G358.93−0.03 fall into the frequency range of the planned high-frequency receivers of the Italian VLBI network (e.g. 20.9, 23.12, 45.8, and 94.8 GHz in Breen *et al.* 2019a; MacLeod *et al.* 2019). The simultaneous observation of all these maser lines is critical because it can reveal the overall picture of the bursting region and unfold the place of rare masers in it. In terms of response to an accretion burst, high-frequency receivers have another advantage. H_2O masers at 22 GHz are known to flare later than methanol masers, which gives ample time to prepare for possible observations (while observations of low-frequency methanol masers have to be done immediately).

The VLBI study of the accretion burst in G358.93−0.03 provided a glimpse into the fine structure of the accretion disk around the massive star, for the first time revealing a strong evidence of the presence of spiral arms in it (Burns *et al.* 2023). It is noteworthy that the success of the “heatwave mapping” method used in Burns *et al.* (2023) depends more on the observation cadence than on spatial resolution. Given the short time scale of accretion bursts and associated maser flares, a great degree of flexibility is required of a VLBI facility in order to capture the “golden hour” of maser flares and accretion bursts. An improvement in the response times of VLBI arrays, possibly related to greater automation of the observational preparation process, could be of great importance for the study of new bursts.

Although VLBI facilities provide the highest resolution insight into flaring masers (e.g. Burns *et al.* 2020a), the VLA is indispensable for providing an overall picture of the region, observing different masers and cm-continuum simultaneously, and detecting weak (and often rare) masers not accessible to VLBI imaging (e.g. Bayandina *et al.* 2019; Chen *et al.* 2020a; Bayandina *et al.* 2022a,b). Another important moment is that the VLA requires shorter observing times and provides the data quicker than any VLBI array, which is essential in case of transient events. Thus, future observations of potential sources of accretion bursts depend heavily on the availability of the observing time with the VLA.

In summary, masers are a sensitive and highly informative probe of star formation. They follow different stages of stellar evolution and alert us to such short-lived and rare events as accretion bursts. The recent years since the discovery of the first accretion burst have shown that the key to the successful search and study of accretion bursts with maser sources is collaboration. The collaboration between experts from different fields (e.g. IR, VLBI, theory) as well as between different facilities (from single-dish monitoring stations to VLBI arrays) has already brought new, impressive results described in this article. The accumulated experience and new upcoming facilities allow us to be optimistic that there is more to come.

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References

Bayandina, O. S., Burns, R. A., Kurtz, S. E., *et al.* 2019, *ApJ*, 884, 140
Bayandina O. S., Brogan, C. L., Burns, R. A. *et al.* 2022a, *AJ*, 163, 83
Bayandina O. S., Brogan, C. L., Burns, R. A. *et al.* 2022b, *A&A*, 664, A44
Breen S. L., Sobolev A. M., Kaczmarek J. F., *et al.* 2019a, *ApJ* (Letters), 876, L25
Brogan C. L., Hunter, T. R., Cyganowski, C. J., *et al.* 2018, *ApJ*, 866, 87
Brogan C. L., Hunter, T. R., Towner, A. P. M., *et al.* 2019, *ApJ*, 881, L39
Burns R. A., Sugiyama, K., Hirota, T., *et al.* 2020a, *Nature Astronomy*, 4, 506
Burns R. A., Orosz, G., Bayandina, O., *et al.* 2020b, *MNRAS*, 491, 4069
Burns R. A., Kobak, A., Caratti o Garatti A., *et al.* 2022, EVN Mini-Symposium 2021, 19
Burns R. A., Uno, Y., Sakai, N., *et al.* 2023, *Nature Astronomy*, 7, 557
CHIME/FRB Collaboration, *et al.* 2021, *ApJS*, 257, 59
Caratti o Garatti A., Stecklum, B., Garcia Lopez, R., *et al.* 2017, *Nature Physics*, 13, 276
Chen X., Sobolev, A. M., Ren, Z.-Y., *et al.* 2020a, *Nature Astronomy*, 4, 1170
Chen X., Sobolev, A. M., Breen, S. L., *et al.* 2020b, *ApJ* (Letters), 890, L22
Chen Z., Sun W., Chini R., *et al.* 2021, *ApJ*, 922, 90
Ellingsen S. P., Voronkov M. A., Cragg D. M., *et al.* 2007, *Astrophysical Masers and their Environments*, 213
Fujisawa K., Yonekura Y., Sugiyama K., *et al.* 2015, *ATel*, 8286, 1
Greif T. H. 2015, *Computational Astrophysics and Cosmology*, 2, 3
Hirota T., Cesaroni, R., Moscadelli, L., *et al.* 2021, *A&A*, 647, A23
Hosokawa T., Yoshida N., Omukai K., *et al.* 2012, *ApJ* (Letters), 760, L37
Hunter T. R., Brogan, C. L., MacLeod, G., *et al.* 2017, *ApJ* (Letters), 837, L29
Hunter T. R., Brogan, C. L., MacLeod, G., *et al.* 2018, *ApJ* (Letters), 854, 170
MacLeod, G. C., Gaylard, M. J. 1996, *MNRAS*, 280, 868
MacLeod G. C., Smits, D. P., Goedhart, S., *et al.* 2018, *MNRAS*, 478, 1077
MacLeod G. C., Sugiyama, K., Hunter, T. R., *et al.* 2019, *MNRAS*, 489, 3981
Meyer D. M. A., Vorobyov, E. I., Elbakyan, V. G., *et al.* 2019, *MNRAS*, 482, 5459
Minier V., Ellingsen S. P., Norris R. P., *et al.* 2003, *A&A*, 403, 1095
Moscadelli L., Sanna, A., Goddi, C., *et al.* 2017, *A&A*, 600, L8
Moscadelli L., Sanna A., Goddi C., *et al.* 2020, *A&A*, 635, A118
Olech M., Szymczak, M., Wolak, P., *et al.* 2020, *A&A*, 634, A41
Proven-Adzri E., MacLeod G. C., Heever S. P. v. d., *et al.* 2019, *MNRAS*, 487, 2407
Sobolev A. M., Moran, J. M., Gray, M. D., *et al.* 2018, *ApJ*, 856, 60
Stecklum, B., Caratti o Garatti, A., Hodapp, K., *et al.* 2018, Proceedings of the IAU Symposium 336, 37
Stecklum B., Wolf, V., Linz, H., *et al.* 2021, *A&A*, 646, A161
Sugiyama K., Saito Y., Yonekura Y., *et al.* 2019, *ATel*, 12446, 1
Szymczak M., Olech M., Sarniak R., *et al.* 2018a, *MNRAS*, 474, 219
Szymczak M., Olech, M., Wolak, P., *et al.* 2018b, *A&A*, 617, A80
Tapia M., Roth M., Persi P., 2015, *MNRAS*, 446, 4088
Volvach A. E., Volvach L. N., Larionov M. G., *et al.* 2020, *MNRAS*, 494, L59
Yang K., Chen, X., Shen, Z.-Q., *et al.* 2019, *ApJS*, 241, 18
Zinnecker H., Yorke H. W., 2007, *A&A*, 45, 481