DOI: 10.18727/0722-6691/5357

Report on the EAS Special Session

The Millimeter Transient Sky: Present Opportunities and Perspectives

Special Session held at the EAS Annual Meeting 2023 in Krakow, Poland, 10–14 July 2023

María Díaz Trigo[1]
Thomas Maccarone[2]
Alex Tetarenko[3]

[1] ESO
[2] Texas Tech University
[3] University of Lethbridge

Time-domain astronomy was identified as a key science area in the US Astro2020 Decadal Survey and is one of the active support areas of ASTRONET. Consistent with these priorities, dedicated facilities are being constructed for studying the variable sky. However, at millimeter wavelengths, only recently have such studies lifted off thanks to the advent of the Atacama Large Millimeter/submillimeter Array (ALMA), with unprecedented sensitivity, and of upgrades of other existing millimetre observatories. The advances in this field and how to overcome the associated challenges were the subject of a special session at the 2023 European Astronomical Society Annual Meeting.

Motivation

The millimetre bandpass is often thought of as being predominantly for studying cool, thermal emitters, like molecular clouds, protoplanetary discs, dust, and the cosmic microwave background (CMB). Such objects must be physically large in order to reach the brightness temperature limits of most millimetre-band facilities, and hence only weakly variable on sub-week timescales. However, the millimetre band also probes synchrotron emission and optically thin free-free emission effectively. Sources emitting via these processes often vary quickly and dramatically. The millimetre band tends to rise earlier and vary more sharply than the radio band (Figure 1), while being less susceptible to interstellar absorption and contamination from blackbody emission than the infrared band. The millimetre emission is also often quite short-lived, requiring either highly responsive Target of Opportunity (ToO) observations, or, for brighter events, very wide field coverage. Time-domain astronomy has grown immensely in the past years as wide-field surveys and sensitive time-domain follow-up facilities have been produced. It was identified as a key science area in the US Astro2020 Decadal Survey[1] and is one of the active support areas of ASTRONET[2]. At millimetre and submillimetre wavelengths, however, the field is still in its infancy. Narrow fields of view of millimetre instruments have precluded serendipitous discovery of millimetre-band transients, and operational challenges in obtaining fast triggers have hampered studies of transient events discovered at other wavelengths. With higher angular resolution, more sensitive CMB surveys, millimetre-band selection of transients has started (Guns et al., 2021) and should accelerate with projects like CMB-S4[3]. Similarly, response times for millimetre follow-up have improved considerably, and could continue to improve.

Special session SS40 at the European Astronomical Society 2023 Annual Meeting showcased recent advances in our understanding of the millimetre variable sky and allowed discussions with staff from millimetre observatories on strategies to enable time-sensitive observations via new processes and policies. The discussions clearly established that the science enabled by such rapid-response science is compelling.

Science opportunities

The session included invited and contributed talks on magnetars, Fast Radio Bursts (FRBs), gamma-ray bursts (GRBs), X-ray binaries (XRBs), pulsars, supernovae, young stars and active galactic nuclei (AGN).

Accretion processes and associated events like launching of relativistic jets in XRBs, accreting millisecond pulsars, AGN or tidal disruption events are undoubtedly one of the main time-domain topics in the millimetre. Precise timing of multi-wavelength variability including flares allows the relative position of emitting regions along the jet to be established, leading to a better understanding of jet propagation and the role of shocks by constraining regions of energisation (for example, Abdo et al., 2010; Tetarenko et al., 2021) and ultimately allowing important jet properties like collimation angle and speed to be determined. Variability of the magnetic field strength and geometry via evolution of the degree of polarisation (Hughes et al., 2023; Myserlis et al., 2018) and of the jet frequency break from optically thick to thin emission (observed in XRBs in real time during accretion outbursts; Russell et al., 2014) are crucial to further investigate how jets are launched and quenched. Finally, exciting science opportunities in this field are linked to the availability of Very Long Baseline Interferometry (VLBI) capabilities, which have already revealed, for example, a rapidly changing (minutes to hours) jet orientation in a stellar-mass black hole at lower frequencies (Miller-Jones et al., 2019).

Outflows in general are one of the products of explosions, stellar collapse or gravitational wave mergers. Studies of the millimetre emission including polarisation of well-known transients like GRBs or recently discovered ones like Fast Blue Optical Transients shortly after the event are crucial to disentangling the different components of emission, such as reverse and forward shocks in GRBs (Laskar et al., 2018). Spectral line observations provide the opportunity to identify the host galaxies of these events, thanks to the presence of molecular and cooling lines from the interstellar medium at all redshifts in the millimetre band (for example, de Ugarte Postigo et al., 2020).

Finally, accretion processes are also at the core of variability around young stars, one of the object classes mostly studied at (sub-)millimetre wavelengths given the presence of thermal dust (from the outer disc and the envelope), free-free emission from the jet and possible gyro-synchrotron emission from magnetic reconnection events which are bright in this wavelength regime (Wielgus et al., 2022). Time-resolved observations on timescales from minutes to years (for example, Fischer et al., 2023) are needed to explore circumstellar geometry and physical structure following heating from accretion (Lee et al., 2020) or changes in disc chemistry following X-ray flares (Cleeves et al., 2017), while longer-cadence monitoring is needed to understand binary interactions between magnetospheres or winds from young stars (for example, Salter et al., 2010).

Challenges

The discussion panel at the special session was composed of Liz Humphreys (chair, ALMA), Adam Hincks (Atacama Cosmology Telescope), Garret Keating (Submillimeter Array [SMA]) and Venkatessh Ramakrishnan (new generation Event Horizon Telescope).

A series of challenges for millimetre time-domain studies were identified, with some being common to all wavelengths (Middleton et al., 2017) and a few particular to millimetre observatories. In what follows we discuss the latter together with potential mitigations.

Obtaining observing time. The rarity of some of the transient phenomena and the need to obtain multi-wavelength observations imply that resources of the scientific teams are typically spread over many observatories, resulting in only few proposals per wavelength range and class of objects, often without a millimetre expert on their teams. For example, while GRBs are a popular astronomical topic, only a handful of proposals are received at ALMA per cycle. This often results in diverse science being classified under ‘time-domain’ and being evaluated by reviewers with expertise in a wide range of classes of objects, and perhaps even competing against each other in distributed review processes, making it more challenging to obtain observing time. This was recognised as a severe problem for highly oversubscribed observatories like ALMA. Soliciting observations of rare events under Director’s Discretionary Time is instead positively regarded by medium-size telescopes like the SMA in the context of expanding their scientific areas to novel topics.

Potential mitigations include:
- Ensure that experts evaluate the proposals by defining the keywords in a more flexible way and widening the range of keywords.
- When possible, submit first proposals to medium-size observatories as pilots.
- Perform observations that show the capabilities of new modes to catch the attention of the community.
- Use the possibilities offered by some observatories to request observing time in two or more observatories via Joint Proposals (for example ALMA–James Webb Space Telescope, ALMA–Very Large Array or ALMA–Very Large Telescope) and have the coordination done by the observatories to reduce overheads. Given the prevalence of high-energy emission among millimetre transients, some consideration should be given to including joint calls with X-ray observatories.
- Memoranda of Understanding can help boost specific nascent fields, for example correlating with AGN/neutrino events, gravitational waves or pulsar timing arrays.
- Provide observatory support for preparing proposals and setting up the observations.

Understanding of constraints and scheduling by the observatories. Besides fast reaction times for ToOs, some time-domain science cases require monitoring over timescales longer than the usual yearly cycle of proposals. Others require multi-observatory coordination with rapid response times. These constraints add to other constraints inherent in the millimetre wavelength regime (for example, the need for superb weather for high-frequency submillimetre observations) or observational technique (for example, the need for a specific array configuration for interferometric observations). While time-domain users are often sensitive to the need to relax some constraints when the time constraint is fulfilled, this is not always allowed by observatory policies (for example, changing the observing frequency if the weather is not good enough for the originally requested frequency).

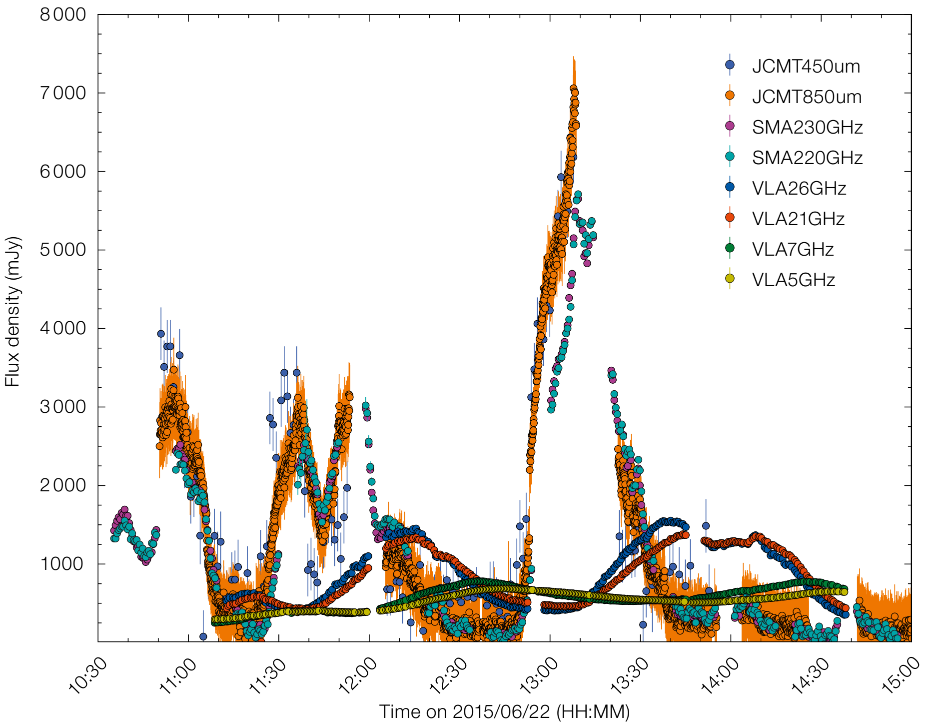

Figure 1. Simultaneous radio through submillimetre lightcurves of the black hole XRB V404 Cygni during the most active phase of its June 2015 outburst. These lightcurves sample the brightest flares at these frequencies over the entire outburst. All lightcurves are sampled at the finest time resolution possible, limited only by the correlator dump time (and the sensitivity for James Clerk Maxwell Telescope [JCMT] data). The Very Large Array lightcurves have two-second time bins, the SMA lightcurves have 30-second time bins, the JCMT Submillimetre Common-User Bolometer Array 2 (SCUBA-2) 350-GHz (850-μm) lightcurve has five-second time bins, and the JCMT SCUBA-2 666-GHz (450-μm) lightcurve has 60-second time bins. The millimetre/submillimetre regime samples a much more extreme view of the flaring activity than the radio regime, with detailed substructure detected only in the millimetre/submillimetre lightcurves. (From Tetarenko et al., 2017, reproduced with the permission of the author).

Potential mitigations include:
– Explore the possibility of carrying over proposals with a low triggering probability over two or more cycles.
– Offer the possibility to relax constraints other than the time-related one at the moment of triggering to enhance observability.
– Automate procedures as far as possible and have a contact person at the observatory to iterate with the user on scheduling possibilities or array availability upon triggering to enable fast reactions.
– Offer multi-cycle proposals for long timescales monitoring programmes.
– Offer ToO capabilities for phased-array and VLBI modes.

Observing cadence and scheduling priority. Given the increase in time-domain observations, establishing adequate observing priorities is crucial, especially for events requiring high-cadence monitoring for a few days or weeks after the trigger.

Potential mitigations include:
– Request estimates of triggering probability from the users so that the observatory can establish priorities relative to other observations based on the rarity of events.
– Explore the use of small arrays (like the Atacama Compact Array in ALMA) for localisation and high-cadence monitoring of bright transients.

Time sampling. A few of the phenomena can only be studied with sub-second (nanosecond to millisecond) time sampling. While fast time sampling is not offered by many millimetre observatories, it is often technically possible and can be enabled with minor operational changes. This is key, for example, for studies of pulsars, such as that of Torne et al. (2021), who performed the first survey unaffected by scattering and therefore unbiased in population coverage at the Galactic centre at 2 and 3 millimetres via time series with 100-microsecond resolution.

Multi-frequency sub-arraying capability raises the possibility of using time-correlation techniques for phenomena with second and subsecond variability, including the Sun.

Real-time light curves. Especially for wide-field and all-sky survey millimetre telescopes like the upcoming Simons Observatory[4], making hourly to daily light curves accessible to the community could be a game-changer for the discovery of millimetre transients. Such light curves must be accompanied by algorithms matching variable sources to multi-wavelength catalogues and notifications to the community, ideally in a standard format agreed by the community and readable by automatic text processing tools.

Real-time data delivery. Monitoring observations of transients (for example of a GRB afterglow) over the days and weeks following the first trigger depend on the brightness and evolution of the event, both often difficult to predict. In this context, 'real time' data processing for quick look data, including for phased-array and VLBI modes, and communication to PIs are crucial to avoid wasting observatory time.

Technical issues. For long-timescale monitoring, flux calibration uncertainties must be well known and as small as possible (for example, less than a percent for stellar occultations). Moreover, interferometric monitoring spanning months or years could be impacted by changes in array configuration leading to missing flux in extended configurations. Finally, the calibration accuracy needed for polarimetry, a powerful tool for studies of millimetre variable objects, is often not sufficient for the low (less than a percent in some cases) levels of polarisation.

Outlook

The enormous potential of time-domain studies in the millimetre has only recently been unveiled. However, the characteristics inherent in such studies make it necessary to implement some changes in the operation of millimetre telescopes to fully exploit this potential. These changes are pressing in light of upcoming facilities like Vera C. Rubin Observatory, expected to discover millions of transients every night, but also of planned sensitive, wide-angle, facilities at millimetre wavelengths like AtLAST[5] or CMB-S4, which will open up the millimetre transient discovery space.

Acknowledgements

We are indebted to the Scientific Organising Committee (SOC), the invited and contributed speakers and the discussion panel for sharing their insights and vision for opening the millimetre window to the variable sky.

SOC: María Díaz Trigo (ESO, Germany), Thomas Maccarone (Texas Tech University, USA), Alex Tetarenko (University of Lethbridge, Canada), Rob Fender (Oxford University, UK), Doug Johnstone (NRC-Herzberg, Canada), Venkatessh Ramakrishnan (University of Turku, Finland), Pablo Torne (IRAM, Spain), Susanna Vergani (Paris Observatory, France)

Invited speakers: Agnes Kospal (Konkoly Observatory, Hungary), Tom Russell (INAF, Palermo, Italy), Ioannis Myserlis (IRAM, Spain) and Antonio de Ugarte Postigo (Côte d'Azur Observatory, France)

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Links

1 US Astro2020 Decadal Survey: https://science.nasa.gov/astrophysics/resources/decadal-survey/2020-decadal-survey/
2 ASTRONET webpage: https://www.astronet-eu.org/
3 CMB-S4 webpage: https://cmb-s4.org/
4 Simons Observatory webpage: https://simonsobservatory.org/
5 AtLAST webpage: https://www.atlast.uio.no/