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Radio Transients in the Era of Multi-Messenger Astrophysics

WORKSHOP 1

G. E. Anderson[1], **B. W. Stappers**[2], **I. Andreoni**[3], **M. Caleb**[2], **D. Coppejans**[4], **S. Corbel**[5], **R. P. Fender**[6], **M. Giroletti**[7], **M. L. Graham**[8], **K. V. Sokolovsky**[9] and **P. A. Woudt**[10]

[1]Curtin University, Perth, Australia
email: gemma.anderson@curtin.edu.au
[2]School of Physics and Astronomy, The University of Manchester, UK
[3]Swinburne University of Technology, Australia
[4]Northwestern University, Evanston, USA
[5]Laboratoire AIM, CEA Saclay, Gif-sur-Yvette, France
[6]Astrophysics, Department of Physics, University of Oxford, UK
[7]INAF, Istituto di Radio Astronomia di Bologna, Italy
[8]University of Washington, Seattle, USA
[9]IAASARS, National Observatory of Athens, Greece
[10]Department of Astronomy, University of Cape Town, South Africa

Abstract. Radio emission from astrophysical transients allows us to derive calorimetry of kinetic feedback and detailed imaging in ways that are not possible at other wavelengths, and as such it forms an important part of the multi-messenger follow-ups of these events. The field is burgeoning, with a renaissance of interest in accretion, stellar explosions and jetted supernovæ, alongside newer classes of phenomena such as fast radio bursts and tidal disruption events. The purpose of this workshop was to discuss the infrastructure and techniques for detecting, identifying and probing radio transients, with a particular focus on how best to exploit transient alerts from multi-messenger facilities. We examined the type of transient alerts those facilities will broadcast, and methods for following them up, such as rapid-response triggering and shadowing. In break-out groups, participants chose a science question related to a particular radio transient type or class and discussed whether the planned transient strategies and observing techniques on the Square Kilometre Array will be adequate to address the particular question. The classes they chose included fast radio bursts, supernovæ, cataclysmic variable and unknown transients. Any proposed adaptation or suggestion was relayed to a panel of experts for further discussion. The second part of the workshop concentrated on the application of long baseline interferometry for detecting and measuring radio transients.

Keywords. Radio continuum: transients, radio continuum: stars, supernovæ: general, cataclysmic variables, fast radio bursts

1. Introduction

The radio Universe is a dynamic place, as many types of transient astronomical sources are known to produce bright radio emission. There are two main classes of radio transients: (1) incoherent or *slow* transients, including explosive and accreting sources such as supernovæ, gamma-ray bursts, X-ray binaries, tidal disruption events and flare stars, with radio emission evolving on time-scales of minutes to days, and (2) coherent or *fast* transients that evolve on milli-second to second time-scales, such as rotating radio transients (RRATs) and fast radio bursts (FRBs); the latter are still an enigma. This radio emission allows us to study shocks and particle acceleration, and to probe total energy budgets, magnetic fields and the structure of the ejecta, the interstellar and the intergalactic media. The two classes require different observing strategies in order to detect and capture their short-lived radio emission.

We are now entering the era of multi-messenger astrophysics, through the development of new facilities capable of detecting gravitational-wave, neutrino and high-energy (TeV) transient events. We must ask ourselves if we are prepared to respond to these exiting events by exploiting the full capabilities of current and future radio facilities, thereby enabling us to obtain the most interesting science. Section 2 below discusses the radio follow-up of multi-messenger events in the context of current infrastructure. Section 3 then examines ways in which we could improve transient science with the Square Kilometer Array (SKA).

2. The Current Infrastructure

As we move into the era of large-scale astronomical facilities such as the SKA and the Large Synoptic Survey Telescope, we notice a significant focus on developing infrastructure specific to transient science. Such infrastructure includes the communication and parsing of transient alerts, and automatic rapid-response observing modes. However, we need to consider whether the infrastructure for our current and future facilities will be capable of addressing our scientific questions.

2.1. *Transient alert notices*

With many more telescopes and multi-messenger facilities now broadcasting transient events automatically, it may become important to standardise the alert notice system across all facilities. One such initiative is the VOEvent protocol, which is a transient distribution standard supported by the International Virtual Observatory Alliance (IVOA). VOEvents are broadcast as XML packets over a decentralised peer-to-peer network, allowing an easy feed-back of messages to the network from a responding robotic telescope. The IVOA welcomes feedback on the development of the VOEvent protocol, so the following improvements may be considered:

- What is the essential information we require in a transient alert notice (e.g. event type, position, etc)?
- The current structure of transient alert notices are instrument dependent. It may therefore be helpful to standardise the notice structure by transient object type. One example is the VOEvent standard proposed for FRBs, which specifies the essential parameters of the event and where that information should appear in the event structure so that it can be ingested automatically into the FRB catalogue (Petroff *et al.* 2017b).
- How do we deal with hundreds of transient detections in a night? One suggestion is that we need better transient classifiers.
- What information is it important to share? For example, many facilities send transient alerts but they never receive a reply. It is important for multi-messenger facilities to know whether their alerts receive responses and if anything was detected in a follow-up.
- Do we need a transient multi-wavelength database that can be built automatically out of transient alert notices? This could (for instance) enable the automatic generation of a spectral energy distribution for each transient, and could appear in a database similar to Simbad.

2.2. *Realising our key science goals*

In an attempt to realise our key science goals, we need to consider the capabilities of the radio telescope. Those capabilities include the response time-scales, the intrinsic time resolution, sensitivity, the cadence of follow-up observations, and the mode of operation. For example, gravitational waves are expected to emit at least four different sources of electromagnetic radiation on very different time-scales, from milliseconds to years following the event (Chu *et al.* 2016).

2.3. *Conflicting alerts from the same transient event*

As more facilities come on-line, each transmitting its own transient alerts, it is possible that some will detect the same transient event. For example, the first detection of gravitational waves from a merging neutron binary star was also detected by the *Fermi* Gamma-ray Burst Monitor (GBM) 1.7 s later (GW 170817/GRB 170817A Abbott *et al.* 2017). However, the gravitational-wave alert notice was not circulated until 27 minutes following the merger. This demonstrates the need for pipelines capable of combining rapidly transient alert notices of the same event from different facilities, using temporal and spatial coincidences.

2.4. *Transient observing modes with radio telescopes*

Rapid-response radio telescopes: Rapid-response observing modes enable radio telescopes to trigger on transient alerts, such as high-energy transients detected by the satellite *Swift*, allowing the telescope to re-point and begin observing the event within seconds to minutes of the detection. While such automated systems are common for optical telescopes, they are very rare for radio telescopes. The system on the Arcminute Microkelvin Imager (AMI) is the longest-running rapid-response programme on a radio telescope. It listens to the *Swift* VOEvent stream via the 4 Pi Sky VOEvent Broker, which parses VOEvent packets, allowing the creation, filtering and archiving of notices (Staley & Fender 2016). It has enabled AMI to trigger on over 300 *Swift*-detected gamma-ray bursts (Anderson *et al.* 2018), with successful detections of early-time radio transient emission (e.g. Anderson *et al.* 2014; Fender *et al.* 2015). Other radio telescopes are now installing rapid-response observing systems, many of which also use the 4 Pi Sky VOEvent Broker, including the Australia Telescope Compact Array (ATCA), the Low Frequency Array Responsive Telescope (LOFAR), and the Murchison Widefield Array (MWA; e.g. Kaplan *et al.* 2015).

Shadowing observing modes: There are now several programmes that use coordinated observing or shadowing modes to detect radio transients. One such programme is Deeper Wider Faster, which coordinates up to 70 telescopes around the Globe to observe a single field, collecting multi-wavelength data from radio to gamma-ray wavelengths. Its main aim is to detect unusual fast transients, particularly shorter-wavelength counterparts to FRBs. It uses pipelines capable of detecting transients in near-real time (Andreoni *et al.* 2017). Another shadowing programme is MeerLICHT (Bloemen *et al.* 2016), the optical telescope that will be slave to MeerKAT, the South African SKA pathfinder telescope. It is only through simultaneous, multi-wavelength follow-ups that we can begin to probe and understand transient physics.

Commensal observing modes: There are now several wide-field radio facilities capable of searching for radio transients in real time. One is the Amsterdam-ASTRON Radio Transient Facility and Analysis Centre (AARTFAAC), which uses the LOFAR core to image the whole sky every few seconds (Prasad *et al.* 2016). The upgraded Molonglo Observatory Synthesis Telescope (UPMOST) is now capable of detecting FRBs (Caleb *et al.* 2017) and will soon be broadcasting FRB alerts in real time.

3. Discussion: Transient Science with the SKA

It is necessary to evaluate the extent to which the planned transient capabilities of the SKA will be able to tackle key scientific questions. The current plan for SKA operations for transient science includes commensal searches using high-time cadence imaging and snap-shot imaging to target slow transients. It is also planned that SKA-mid will be capable of forming tied-array beams with some sub-set of dishes for fast transient (non-imaging) searches in real-time (commensal), in archival mode, and in a multiple mode of up to four tied-array beam VLBI. The detection of transients may also trigger a data freeze and dump from transient buffers (on both SKA-mid and SKA-low), which will contain tens of seconds to minutes of look-back time. Additionally, both SKA telescopes will have rapid-response systems that will trigger follow-ups of internally detected transients (which will be broadcast via VOEvent notices), and external alerts†

Participants at the Workshop divided into groups based on their interest in one of four transient classes: FRBs, supernovæ, cataclysmic variables, and unknown radio transients. The groups were asked to select a science question pertinient to the particular transient type, and were encouraged to consider the following:

- What information is required in a transient alert notice to prepare for a follow-up?
- What technical issues are important for you (e.g., frequency bands, baseline lengths, fields of view *versus* sensitivity)?
- What element of the present system will allow you to meet your science goal?
- What adaptions need to be made to realise your science question?
- How can those adaptions be applied to improve techniques and strategies for observing radio transients with the SKA?

The group discussions were followed by a panel discussion. A summary of the main discussion points and suggestions for improvements to the SKA transient strategy are outlined below for each of the four transient classes.

3.1. *Fast Radio Bursts*

The origin of FRBs is still unknown, yet they are extremely common, with rates obtained by Parkes reaching a few thousand per sky per day (Champion *et al.* 2016; Bhandari *et al.* 2018). There also appear to be two classes of FRB (Petroff *et al.* 2015b; Palaniswamy *et al.* 2018): repeating FRBs, for which only one is known (FRB 121102; Spitler *et al.* 2016), and non-repeating FRBs, where $\geqslant 30$ have been detected (Petroff *et al.* 2016). As rapid multi-wavelength follow-ups of the Parkes FRBs have not yielded a counterpart detection (Petroff *et al.* 2015a, 2017a; Bhandari *et al.* 2018), it is possible that some FRBs may not be caused by a cataclysmic event. The lack of cataclysmic counterparts and the fact that FRB emission is coherent has meant that multi-wavelength efforts now focus on performing shadowing observations of wide-field FRB detectors, which allows any lead-up signals to be detected at optical to gamma-ray frequencies before the FRB is detected in the radio band. Such wide-field FRB survey programmes include UTMOST, the Australian SKA Pathfinder (ASKAP) through the CRAFT (Commensal Real-time ASKAP Fast Transients Survey) programme, MeerKAT through the MeerTRAP programme (Real Time Commensal Searching for Transients and Pulsars with MeerKAT, with MeerLICHT providing simultaneous optical coverage), and the Canadian Hydrogen Intensity Mapping Experiment (CHIME).

As those wide-field and sensitive radio facilities come on-line, there will be a reasonable and burgeoning sample to perform useful FRB population statistics (Macquart & Ekers 2018). It is crucial to localise the events, thereby allowing the host galaxy to be identified.

† SKA baseline design and requirements documents: skatelescope.org/key-documents/

We thereby obtain independent distance measurements that can be compared to those inferred from dispersion measure, providing in turn vital information about the baryonic content of the Universe. In order to localise an FRB detected by the SKA, we recommend that the transient alert trigger an immediate VLBI follow-up via a joint observatory programme in tandem with other radio facilities around the world.

Distinguishing between the two classes of FRBs is also of great interest. In order to identify a repeating FRB detected with SKA, it would be helpful to look back in time to determine if there was a lead-up of fainter precursor FRBs. The SKA-mid and SKA-low transient buffers, capable of holding up to 30 s and 7 mins of data respectively, will enable such searches for potential precursor events. We recommend that, when the buffer is being dumped, the read-out does not prevent further recording as that would impede the detection of repeating FRBs following an initial trigger.

3.2. *Supernovæ*

Type Ia supernovæ(SNe) are thermonuclear explosions of carbon-oxygen white dwarfs that are binary members, but the type of binary companion star remains relatively unconstrained. While observations point to the majority of SNe Ia being double degenerates (e.g., their rates, and clean local environments), at least some exhibit signatures indicating a main-sequence star or a red giant. One of the clearest signatures is the presence of hydrogen-rich circumstellar (CSM) material, but SNe Ia exhibiting optical evidence of CSM interaction are rare ($< 1\%$). Searches for CSM via the radio signature can be a better avenue because it can yield direct constraints on the density and distribution of the CSM, and indicate whether it is (for example) a continuous wind (red giant) or a shell (nova eruptions). This avenue has been attempted (e.g. Hancock *et al.* 2011; Chomiuk *et al.* 2016), but requires a more sensitive radio telescope (the signal from an interaction with a wind has a low luminosity), a longer baseline for the observations (to probe CSM at a greater distances from the white dwarf), and a larger number of SNe Ia in the nearby volume (to increase the chance of observing the possibly rare instance of CSM around a SN Ia). SKA-mid appears to be well suited for this kind of follow up owing to its sensitivity and bandpass coverage. Rapid turn-round is not necessary for this type of investigation, and the snapshot-style trigger would work well. A dedicated, targeted survey of nearby SNe with SKA could yield the first-ever detection of a SN Ia with CSM interaction at radio wavelengths.

3.3. *Cataclysmic Variables*

Cataclysmic Variables (CVs) are thought to be binary stars in which a white dwarf accretes material from a low-mass main-sequence star via Roche-lobe overflow. We have only recently had the sensitivity required to detect CVs at radio wavelengths. Their radio emission is typically of the order of $10\times$ to many $100\times$ μJy at GHz frequencies and has been observed to vary on time-scales of days down to ~ 200 secs (Körding *et al.* 2008; Coppejans *et al.* 2015; Russell *et al.* 2016; Coppejans *et al.* 2016; Mooley *et al.* 2017). However, the sensitivity of current instruments is too low to obtain spectral indices or to perform VLBI in order to image the radio-emitting structures. More sensitive radio observations, when combined with simultaneous multi-wavelength observations (optical, UV and X-ray), over the course of an outburst in multiple systems, are required to test whether CVs are launching jets (Körding *et al.* 2008).

The ThunderKAT project has both dedicated time and also commensal access to the large survey data from MeerKAT for CV science. When combined with the simultaneous optical data for every pointing by MeerLICHT, it will be ideally suited to perform these observations. There is on-going discussion about how to utilise the dedicated ThunderKAT CV time. CVs will be found in the large survey deep-field data, but at present it is not clear how many CVs are in those fields, and an optical survey is necessary to identify candidates. The most effective use of the dedicated time seems to be to make high-cadence observations of 1 or 2 systems in order to map fully the outburst behaviour, variability and spectral indices. As almost all CV detections to date were obtained with the VLA, a snap-shot survey of the nearby southern CVs will need to be performed with MeerKAT first to select candidates. SKA-mid will be well suited to CV science as its higher frequency coverage will be ideal for probing synchrotron and gyrosynchrotron flaring radio emission, which is brighter and varies on shorter timescales with increased frequency. When snap-shot imaging mode is employed to monitor a large number of CVs (potentially using subarrays), flaring behaviour can be identified quickly, allowing internal triggering with the full SKA and/or rapid-response follow-ups with other facilities.

3.4. *Unknown radio transients*

To determine whether an unknown radio transient is new or of interest for further follow-up, there needs to be a way of ascertaining whether it is unusual. That requires pipelines capable of identifying radio transient types quickly and to make smart decisions on whether to activate multi-wavelength follow-ups. There is therefore a need for multi-wavelength cross-discipline expertise to optimise this discovery space. Multi-wavelength slave instruments (similar to MeerKAT and MeerLICHT), and rapid-response instruments ready to receive SKA triggers, are vital to unveiling the unexpected and unknown radio transients.

4. Investigating Radio Transients with VLBI

The technique of Very Long Baseline Interferometry (VLBI) can provide accurate localisation and unique physical information about radio transients. However, it is still under-utilised owing to the inherent difficulties of VLBI data analysis and practical difficulties of organizing observations on short notice. We present a summary of the techniques, including a discussions of observing strategies that are currently used to study long- and short-duration radio transients. A catalogue of VLBI arrays and their properties is given in the on-line version [https://doi.org/10.1017/S1743921318003022], together with a list of objects known to generate transient radio events.

The VLBI technique (Walker 1999) combines signals recorded at distant radio telescopes to achieve the highest angular resolution. A typical VLBI scale of 1 mas by definition corresponds to the linear size of 1 AU at the distance of 1 kpc and 1 pc at $z \sim 0.05$. The longer the baseline (distance) between the elements, the higher is the interferometer's angular resolution. Another way to increase angular resolution is to observe at a shorter wavelength. The measured interferometer response may be compared to a simple model in order to estimate the source size and flux density or, if measurements at many baselines are available, the source image may be reconstructed.

The following features of VLBI may provide insights into the nature of various astrophysical transients:

- Superb angular resolution helps to measure the source size.
- Accurate localisation of the radio emitting site is possible with VLBI.
- Imaging reveals the radio emitting region geometry (jet/shell/shock front) and allows us to follow its changes (proper motion, expansion).

• Full Stokes imaging may provide clues about the mechanism responsible for the transient's radio emission and, in the case of synchrotron transients, measure the magnetic field strength and structure.

• VLBI can separate the (small) transient source from the unrelated background emission that will be 'resolved out', no matter how bright the background is.

4.1. *Observing strategies*

While, in principle, wide-field VLBI imaging (Morgan *et al.* 2013) may be used to *search* for slow transients, the most popular observing strategy so far is the *follow-up* of transients discovered at other wavelengths.

The two key points to consider when planning observations are the array sensitivity and the possibility of rapid response. A sensitive array includes big dishes and is capable of performing phase-referencing observations. Phase referencing makes the integration time (and hence the sensitivity) limited by the experiment duration rather than the atmosphere coherence time. Dedicated full-time arrays like VLBA and KVN, as well as ad hoc arrays including only two to three telescopes can respond within days to a trigger (if the corresponding observing proposal is already in place). VLBI observations often rely on the Earth's rotation to probe more spatial frequencies as the array elements move and improve the resulting image. This technique cannot be used for rapidly evolving transients. A 'snapshot' observation will result in a degraded image (compared to a 'full track' image) or may be suitable only for modelling, not image reconstruction. The quality of a snapshot image may be improved by adding more elements to the array. Another point to consider for Galactic transients is their expected angular size.

An explosive transient may take hours to days to reach the angular size of a few mas and become 'too big' to be observed with VLBI. Unless it has a structure on smaller angular scales, it may be completely 'resolved-out' by the interferometer. The choice of observing frequency is less important than other considerations when observing synchrotron transients as they tend to have nearly flat spectra.

With the exception of repeating events like FRB 121102 or the ones possessing a long-term 'afterglow', triggered observations of fast transients are not possible. Instead, the fast transients have to be found in the same data used to investigate them. Raw VLBI data (before being averaged in time and frequency by the correlator) are suitable for a fast transient search (Liu *et al.* 2018). The V-FASTR project is running a commensal survey for fast transients at the VLBA (Wayth *et al.* 2011; Wagstaff *et al.* 2016). One interesting possibility is shadowing a large single-dish telescope with a VLBI array, extending the observing strategy of Marcote *et al.* (2017) to a blind survey.

The Square Kilometre Array (SKA) will detect transients in real time, providing targets for a VLBI follow-up. Including the phased SKA into an existing VLBI network will boost the network sensitivity by more than an order of magnitude. This will enable detailed VLBI studies of the classes of sources that are now just barely detectable. Studies of classical VLBI targets such as AGNs will also benefit from access to a larger sample of observable sources an its extension towards low-luminosity objects. An overview of VLBI prospects for the SKA is presented by Paragi *et al.* (2015), while Corbel *et al.* (2015) highlight perspectives for Galactic synchrotron transient studies.

5. An Overview of VLBI Arrays

A catalogue of VLBI arrays and their properties is given in the on-line version [https://doi.org/10.1017/S1743921318003022], together with a list of objects known to generate transient radio events. The majority of arrays listed offer at least part of their observing time as 'open sky' (any astronomer can apply), and also accept requests on the basis of 'targets of opportunity'. Note: the list does not include some telescopes which are capable of VLBI but are dedicated either to space geodesy (Schuh & Behrend 2012) or to deep space communication.

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