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Discovering Radio Transients using ‘Triggered’ and ‘Targeted’ Observations

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Abstract. As the era of the Square Kilometre Array approaches, astronomers are investigating how to make good use of its facilities for studying radio transients. This talk presented two different methods for radio transient discovery – ‘triggered’ and ‘targeted’ observations – which can be used to supplement the blind survey approach. Both techniques focus on performing radio observations of sky regions in which we expect to find radio transients. ‘Triggered’ observations are obtained by telescopes capable of responding rapidly to transient alerts; they automatically repoint and begin collecting data within minutes of the alert being given. ‘Targeted’ observational techniques involve radio monitoring of specific sources or regions such as nearby, face-on galaxies, globular clusters, and the Galactic Plane. Such observations are sensitive to transient radio jets from black holes accreting at, or above, the Eddington limit, with the additional benefit of providing many potential sources within a single field of view. Both observing strategies illustrate important techniques for radio transient discovery that can be employed by the SKA.

Keywords. Radio: monitoring, transients, flares

1. Introduction

As we approach the era of the Square Kilometre Array (SKA), interest in the discovery radio transients is burgeoning. This radio emission is important to observe, as it traces relativistic ejecta and non-thermal processes (enabling us to study shocks and particle acceleration) while probing magnetic fields and the structure of the surrounding interstellar and intergalactic environment. Most studies of radio transient so far have focussed on blind searches for transients in radio surveys and archived data. While important steps have been made towards optimizing and automating such searches, the studies have demonstrated that radio transients are rare and faint, and often evolve over very short time-scales (Stewart *et al.* 2016). I have therefore been investigating alternative approaches for radio transient detection, which I will refer to as ‘triggered’ and ‘targeted’ observations. The aim of those approaches is to perform deep radio observations of sky regions in which we expect to find radio transients, thus complementing the shallow, all-sky, blind surveying method. A detailed description of the triggered radio detection methods is provided in Section 2; targeted ones are described in Section 3 in the context of recent results. Section 4 discusses the implications of these two approaches.

2. Triggered Observations

In transient astrophysics, often the most difficult parameter space to probe is the very beginning of a transient event, when observations are expected to reveal the most interesting physics. While robotic optical telescopes are now very common, and rapid X-ray and gamma-ray follow-ups have become possible with dedicated high-energy transient satellite missions, historically it has been difficult to obtain a prompt follow-up response in the radio band. However, in the lead-up to the SKA we are moving towards optimizing radio facilities so as to make them more competitive in transient work, and to that end rapid-response observing modes are being introduced. Rapid-response observing systems allow telescopes to respond automatically to external transient alert notices, interrupting the current observing programme and repointing at the transient source. This constitutes the start of a triggered observation; such systems enable telescopes to repoint within seconds to minutes on receiving the event information, thus probing the most interesting (early-stage) physics. Having radio telescopes responding to external triggers such as high-energy transients detected with *Swift* and *Fermi*, or gravitational wave events from Advance LIGO and Virgo, offers much higher chances of detecting radio transients, as we will know exactly where to look and can therefore perform deeper observations.

Rapid-response systems have not been common on radio telescopes in the past, but recently there has been a resurgence of interest in this observing mode. The first experiments were conducted with the Cambridge Low Frequency Synthesis Telescope at 151 MHz, which triggered on gamma-ray bursts (GRBs) detected with the Burst And Transient Source Experiment (Green *et al.* 1995, Dessenne *et al.* 1996). More recently, GRB triggering experiments detected by *Swift* have been conducted using single radio dishes (e.g. Bannister *et al.* 2012, Palaniswamy *et al.* 2014), and by interferometers such as the Murchison Widefield Array (MWA, the SKA low frequency precursor based in Western Australia; Kaplan *et al.* 2015), and the Arcminute Microkelvin Imager (AMI) Large Array, based in Cambridge, UK (Anderson *et al.* 2018). Both the Australia Telescope Compact Array (ATCA), based in New South Wales, Australia, and the Low-Frequency Array (LOFAR) in the Netherlands have also recently commissioned rapid-response observing modes.

The system on AMI is the longest-running rapid-response programme on a radio telescope. It listens to the *Swift* VOEvent stream (VOEvent is a standard format for distributing astronomical transient alerts) via the 4 Pi Sky VOEvent Broker, which parses VOEvent packets, allowing for the creation, filtering and archiving of notices (Staley & Fender 2016). On receiving a VOEvent trigger, AMI can be on the target within 2 minutes. Since beginning this programme in 2012, AMI has now triggered on well over 300 *Swift*-detected GRBs (Anderson *et al.* 2018). In fact, triggered AMI observations of *Swift* transients has resulted in one of the earliest detections of a radio afterglow from a long-duration GRB (GRB 130427A; Anderson *et al.* 2014). The triggered observation, combined with follow-up AMI monitoring observations, showed how the radio emission peaked and then faded within one day – behaviour which is characteristic of reverse-shock emission from the shocks created by the GRB jet propagating back into the post-shocked ejecta, rather than a forward shock expanding into the interstellar medium that generates the slower evolving afterglow. AMI also responded rapidly to a *Swift* detection of an X-ray/gamma-ray superflare from the rapidly rotating M-dwarf star DG CVn (Fender *et al.* 2015); AMI was on the target within 6 minutes of receiving the trigger, and observed DG CVn recovering simultaneously from a giant radio flare. This was the earliest detection by a radio telescope of bright, prompt radio emission following a high-energy trigger; the event could be one of the most luminous incoherent flares from an M dwarf yet detected. Fig. 1 shows the rapid-response detections of GRB 130427A and DG CVn.

3. Targeted Observations

The technique of targeted observations for discovering radio transients involves performing radio monitoring of sky regions that have a high density of potential sources within a single field of view. Such regions could include nearby, face-on galaxies, globular clusters and parts of the Galactic Plane. The value of observing nearby galaxies for new radio transients was demonstrated by the recent discovery of a transient ultra-luminous

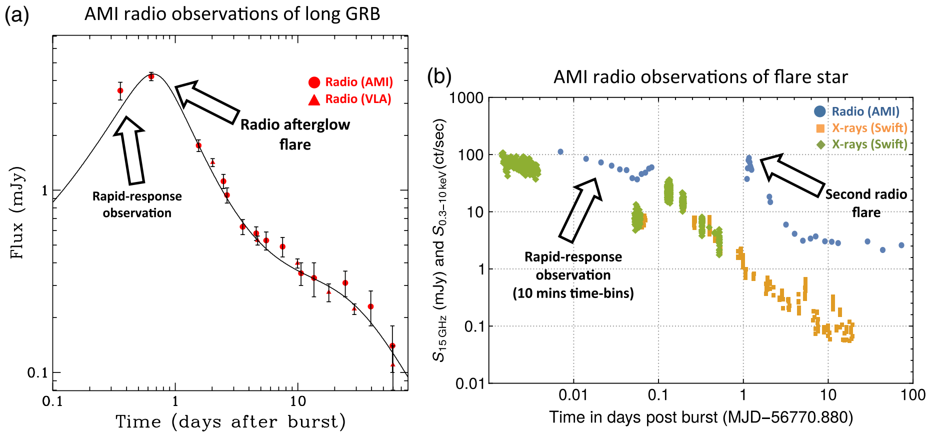

Figure 1. Results using the AMI rapid-response mode. Arrows indicate the rapid-response observations and radio flares. *Left:* Radio emission from GRB 130427A (first published by Anderson *et al.* 2014). This is one of the earliest radio detections of a long-duration GRB. The peak of the radio afterglow flare occurred within 1 day of the *Swift* detection. *Right:* Radio and X-ray emission following the *Swift* detection of a gamma-ray superflare from DG CVn (first published by Fender *et al.* 2015). The first AMI observation occurred <6 minutes following the alert, and detected a giant radio flare. A second radio flare was detected 24 hrs later.

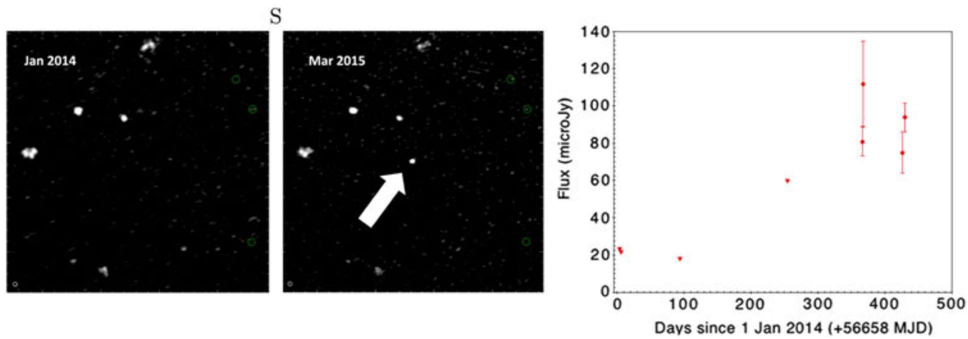

Figure 2. *Left:* VLA images of the transient in M 81 showing a non-detection in January 2014, followed by a detection in March 2015. The transient is indicated by the arrow. *Right:* Radio light-curve of the M 81 transient.

X-ray source (ULX – a black-hole binary accreting at about the Eddington limit) in M 31, that had extremely bright radio jets (Middleton *et al.* 2013). The statistics suggest that there could be one transient (ULX) per galaxy every two years.

Inspired by the detection of jetted radio emission from an accreting source in a nearby galaxy, we explored further the targeted observational technique by performing a two-year monitoring campaign of M 81 using the Very Large Array (VLA). From early 2013 to early 2015 the VLA obtained 12 1-hour snap-shots of each quadrant of M 81 at 6 GHz in a variety of configurations. Such observations are sensitive to radio supernovæ and to transient radio jets from black holes accreting at or above the Eddington limit. A preliminary result was the discovery, in early 2015, of a radio transient, demonstrating the validity of this technique (left panel of Figure 2). While much fainter than radio supernovæ, the radio transient was a factor of 10 more luminous than the transient ULX in M 31. It also showed a stable flux over a 2-month period (right panel of Figure 2), with little evidence of the short-term variability which is usually expected from jets during outburst (e.g. Tetarenko *et al.* 2017). The radio detection of super-Eddington accreting black holes enables us to probe the coupling of the accretion (inflow) and jets (outflows) at the very highest accretion rates, a process that that has only been studied properly in sub-Eddington accreting black holes (e.g. Fender *et al.* 2004, Dunn *et al.* 2010).

4. Implications

The triggered and targeted observing strategies exploit the idea that we should look for radio transients where we expect to find them, thus complementing the all-sky, blind survey approach for transient discovery. The AMI rapid-response programme has demonstrated the power of triggered follow-ups of transients for probing the unexplored parameter space of early-time radio properties (Anderson *et al.* 2014, Fender *et al.* 2015, Anderson *et al.* 2018). The success of this programme has encourage the installation of rapid-response systems onto other radio telescopes, including MWA, ATCA and LOFAR. With its high sensitivity and its multiple frequency and polarization capabilities, the ATCA rapid-response mode will provide unique insight into the early-time properties of short-duration GRBs, which are a subclass of gravitational-wave events. It will also investigate whether coherent radio flares are associated with X-ray/gamma-ray superflares produced by flare stars. At the lower radio frequencies probed by MWA and LOFAR, we can now search for prompt, coherent emission associated with neutron star mergers and flare stars, and perhaps gain a handle on the spectrum of FRBs. The 2-year VLA monitoring programme of the nearby galaxy M 81 has already demonstrated the strength of targeted observations for finding radio transients. One such transient, probably powered by accretion, has already been detected, adding further support to the transient ULX outburst rate proposed by Middleton *et al.* (2013).

Both the triggered and the targeted observational techniques are exploring transients strategies for the SKA. Such observations enable us to probe new parameter spaces, in particular the early-time radio properties of radio transients and accretion-jet coupling at super-Eddington accretion rates.

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