ThunderKAT: The MeerKAT Large Survey Project for Image-Plane Radio Transients

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ThunderKAT is the image-plane transients programme for MeerKAT. The goal as outlined in 2010, and still today, is to find, identify and understand high-energy astrophysical processes via their radio emission (often in concert with observations at other wavelengths). Through a comprehensive and complementary programme of surveying and monitoring Galactic synchrotron transients (across a range of compact accretors and a range of other explosive phenomena) and exploring distinct populations of extragalactic synchrotron transients (microquasars, supernovae and possibly yet unknown transient phenomena) - both from direct surveys and commensal observations - we will revolutionise our understanding of the dynamic and explosive transient radio sky. As well as performing targeted programmes of our own, we have made agreements with the other MeerKAT large survey projects (LSPs) that we will also search their data for transients. This commensal use of the other surveys, which remains one of our key programme goals in 2016, means that the combined MeerKAT LSPs will produce by far the largest GHz-frequency radio transient programme to date.

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1. Introduction

Transient radio emission is associated with essentially all explosive phenomena and high-energy astrophysics in the universe. It acts as a locator for such events, and a calorimeter of their kinetic feedback to the local environment. Because of this, radio transients are invaluable probes for subjects as diverse as stellar evolution, relativistic astrophysics and cosmology. ThunderKAT is the programme to observe such phenomena in the image plane with MeerKAT. It is also the umbrella project behind the MeerLICHT optical telescope [1], which will provide simultaneous optical images for all night-time MeerKAT observations.

2. Accretion physics

Accretion phenomena on all scales and across all environments are associated with the generation of outflows, which reveal themselves via synchrotron radiation in the radio band. Observations of these outflows allow us to test how much kinetic energy is being fed back from the accretion process, and in some cases to directly resolve the fastest-moving bulk phenomena in the universe.

2.1 Relativistic accretion

2.1.1 Black holes and neutron stars in X-ray binaries

Stellar-mass black holes (BHs) in X-ray binary systems provide our best sample with which to understand how varying accretion states affect the power and type of kinetic feedback from BH via winds and jets. The neutron star (NS) X-ray binaries provide the best possible 'control sample' to study which aspects of this behaviour are unique to BH and may therefore be dependent on the existence of an event horizon or ergosphere.

The current fundamental tool for understanding the global connection between accretion and ejection in X-ray binaries is the radio-X-ray plane (Fig 1). Currently the plane is populated by around 200 quasi-simultaneous radio and X-ray observations of X-ray binaries and has led to some key results and even more unanswered questions:

- a strong correlation exists between accretion rate and jet power, which can be extended with the addition of a mass term to include BH of all masses, from X-ray binaries to supermassive black holes in AGN.

- the jet is suppressed in some high-luminosity states (analogues of radio-quiet AGN)

- some neutron stars (the transitional millisecond pulsars) behave like black holes in this plane, whereas others show the steeper correlation expected for radiatively efficient accretion in the presence of a hard surface

- there is a mysterious 'radio quiet' branch where some BH produce less powerful jets under the same accretion conditions (as measured in X-rays) as others.

Note that for sources in bright accretion modes, X-ray monitors (e.g. ASTROSAT, HXMT) will provide good enough measurements to place the MeerKAT data in the plane. For fainter
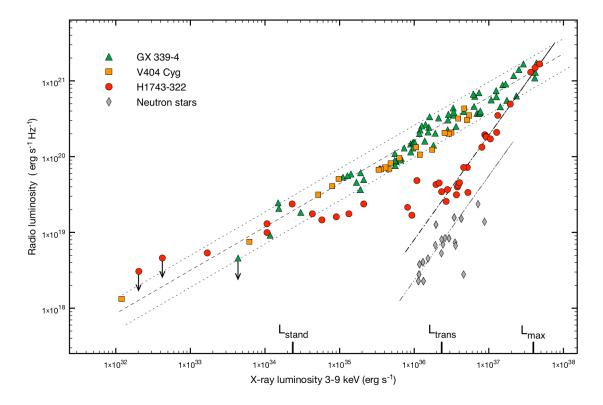
Figure 1: The radio-X-ray plane for black hole and neutron star X-ray binaries [2]. Quasi-simultaneous observations allow us to map out the long-term connection between accretion and ejection. The empirical patterns observed can be scaled to supermassive black holes in AGN, and yet throw up many mysteries. A comprehensive monitoring programme with MeerKAT will increase the number of measurements in this plane by a factor of up to 5, notably probing for the first time the mapping for the neutron star binaries, which are radio-quiet relative to the black holes.

sources we will request e.g. Swift/Chandra/XMM observations quasi-simultaneously with MeerKAT. Because the neutron star X-ray binaries are significantly fainter in the radio band than the black holes [3], it is only with the advent of the SKA precursors that we finally have the potential to map out the radio-X-ray plane for these sources (while the X-rays are just as bright so do not need new facilities). On any given day there will be 1-10 sources of interest to monitor, typically at $0.1 - 10$ mJy flux densities, i.e. readily achievable within an hour (some sources will be much fainter however and require more time).

In addition to the slow evolution of sources in the radio-X-ray plane, X-ray binaries occasionally go into major outbursts, which are associated with radio flaring [4]. These flaring states are associated with powerful, intermittent jet production and, when matched with high-sensitivity X-ray observations and VLBI, are our best hope for understanding the details of the connection between accretion and jet formation. We note that because the sources are typically bright but rapidly varying during these phases, and that it is the comparison with the X-ray data which provides the physical insights, cadence can trump raw sensitivity. In fact, such observations could sometimes be undertaken with a minor subarray of MeerKAT, or even with a refurbished KAT-7.

2.1.2 Tidal disruption events

Tidal Disruption Events (TDEs) result from the catastrophic destruction and subsequent accretion of a star by the gravitational field of a supermassive black hole. They provide our best insight into the response of a supermassive black hole to a sudden increase in mass accretion rate. It now seems that this response may be quite different to the 'steadier' modes that are analogous to X-ray binaries, and yet this could have been the dominant mode during the phases of strongest AGN activity at redshifts 2-3. The current rate of discovery of good TDE candidates is quite low, probably less than 5 per year. The recent detection of weak radio emission from the 'thermal' TDE ASASSN-14li [5] suggests that all TDEs produce radio emission, but that there may be a range of kinetic modes and powers. As with neutron star (above) and white dwarf (below) accretion, the huge sensitivity leap with MeerKAT will allow us to probe a significant number of TDE radio afterglows for the first time (currently five in total).

2.1.3 Ultraluminous X-ray sources

ULX are off-centre X-ray sources in galaxies that have luminosities in excess (in some cases) of the maximum for stellar-mass black holes. They may be our best route to finding the population of intermediate-mass black holes (IMBH) which constitute the path from stellar remnants to supermassive black holes (see also the recent aLIGO results). The best accreting IMBH candidate to date, HLX X-1, has revealed radio flaring indicating transient jet production [6]. A second flaring 'HLX' candidate [7] has since been discovered. Flaring transient ULXs in nearby galaxies also provide a way to probe Eddington-rate accretion, showing how jets couple to the accretion flow in a radiation-pressure dominated environment, as was likely required for the rapid growth of the first quasars.

2.2 White dwarf accretion

2.2.1 Outflows of accretion-powered outbursts of white dwarfs

Cataclysmic variables (CVs) show violent outbursts similar to those outlined above for XRBs, but have as an accretor a white dwarf. It is assumed that outbursts in both classes of objects are triggered by the same disc instability. The similarity between XRBs and CVs is most prominent for dwarf novae (DNe). These non-magnetic, disc-accreting white dwarfs show fairly regular outbursts that are thought to be powered solely by accretion.

Radio emission from CVs had been reported previously but was usually not reproducible. It had thus been suggested that the radio emission is correlated with the optical outburst. This has been confirmed by [8] with a detailed radio light-curve of SS Cyg using MERLIN and VLA. Following the repeatable behaviour of SS Cyg, a subsequent survey by South African PhD student Deanne Coppejans with the JVLA using triggered observations of 5 DNe in outburst yielded a 100% detection rate. The triggers have been provided by amateur astronomers from the AAVSO. Most of these nearby sources (100-260 pc), show flux densities around 15-60 μJy [9]. In addition to these transient CVs, persistent CVs of both magnetic and non-magnetic nature show radio emission [10].

MeerLICHT will greatly enhance the study of accreting white dwarfs. Radio observations will trace the outflowing material of CVs while the optical observations will provide us real time

information on the current state of the accretion disc. MeerLICHT's 1 minute cadence will yield optical fluxes and colours as well as variability information. Unlike in XRBs, the accretion disc in CVs is visible at optical and UV wavelengths. Thus, any night-time radio observation of a CV will allow us to study both the outflow and the accretion flow for the first time truly simultaneously. A MeerKAT in-depth study of a large sample of southern CVs, sampling accreting white dwarfs with a range of different donor stars (from giants to white dwarfs) will determine the radio properties of the population of accreting white dwarfs and will allow for a direct comparison of the outflow properties of non-relativistic accretors with the relativistic black hole and neutron star XRBs.

2.2.2 Outflows in thermonuclear eruptions on white dwarfs

Radio observations can provide the best estimates of the fundamental nova parameters, e.g. distance (via expansion parallax from high resolution imaging), ejected mass and kinetic energy (via modelling radio light curves) and ejecta geometry (via imaging and light curve modelling). The ENOVA program on the JVLA has demonstrated that low frequency radio observations like those that will be made with the initial L-band of MeerKAT, will still provide new insights into the outflow properties of novae as shown by the recent results on T Pyx [11] and V1723 Aql [12]. It is now well understood that in most novae the mass is not ejected in spherically symmetric fashion, but instead shaped in high velocity, strongly collimated bipolar outflows [13, 14].

The need for a southern program can be demonstrated by the recent nova V1369 Cen (2013), which has not been properly covered in the radio, even though it was detected by Fermi/LAT and even visible to the naked eye. KAT-7 observations were attempted with an upper limit of 6 mJy at 1.8 GHz (3 sigma). Through a dedicated ToO programme of Galactic novae with MeerKAT - in combination with simultaneous X-ray and optical/near-infrared observations - we can make critical advances in our understanding of nova ejecta (mass, energetics, nature of the outflow).

2.3 Cosmic explosions

The endpoints of the lives of the most massive stars in the universe are the core collapse supernovae (CCSNe) and gamma-ray bursts (GRBs), the most powerful explosions in the universe. In recent years a picture is beginning to emerge of a continuum of kinetic powers and Lorentz factors, with relativistic, engine-powered CCSNe bridging the gap between classical CCSNe and GRBs (Fig 2, left panel). Our targetted programme is augmented by commensal studies.

2.3.1 Gamma-ray bursts

At all redshifts (currently to $z \sim 8$) half of GRB afterglows are detected in radio with present techniques. This means we can use them as probes of the distant universe, and the star formation process through cosmic history. The special class of short GRBs (duration under 2 s) are thought to result from compact-object mergers and thus also the prime candidates for EM counterparts to gravitational wave events (Sect 2.5).

The connection between (long) GRBs and SNe is still uncertain, and needs to be further explored. According to the best available hypothesis, what makes a GRB different is that it signals the birth of a black hole from a fast-rotating star, which unlike a SN causes significant energy to be emitted as ultra-relativistic jets, giving rise to the spectacularly bright flashes of gamma rays and
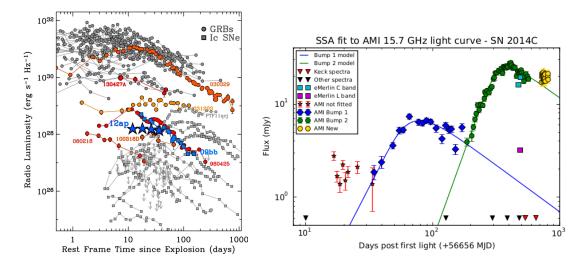
Figure 2: Left panel: The zoo of radio light curves of stellar explosions from classical supernovae (bottom of panel) to GRB afterglows (top of panel), representing a progression from sub- to highly-relativistic outflows. From [15]. Right panel: The extraordinary radio light curve of SN2014 (AMI-LA data). Three, possibly four, peaks have been observed in the radio light curve of this source so far, indicating interactions of the explosive ejecta with a number of discrete shells, providing a unique probe of the last decades (SN ejecta are an order of magnitude faster than the winds which created the shells) of pre-supernova evolution and mass loss of the most massive stars [16].

afterglows lasting days (X rays) to weeks (optical) to years (radio). GRBs are exceedingly rare: only about 1/Myr/galaxy, 10,000 times rarer than SNe. This predicts, among other things, that for every GRB we see, there are 100 whose collimated outflow is not aimed at us. These should be visible as SNe of type Ib/c, for which at late times, when the GRB afterglow becomes non-relativistic and unbeamed, we see a GRB-like radio afterglow. A few recent type Ib/c SNe have shown that a (mildly) relativistic component o f the SN ejecta can sometimes already be observed in the radio a few days after the initial stellar explosion, while a gamma-ray signal has not been detected.

Targeted MeerKAT follow-up of GRBs will help us constrain the GRB physics, determine the true total kinetic energy released, and understand relativistic shocks and particle acceleration in them. Especially for short GRBs, where less than 5 radio afterglows have been seen, this will help greatly in improving our physical understanding of them. Similar follow-up of SNe (Sect. 2.3.2) will allow us to compare this with the non-relativistic version of the same process, and possibly also find the GRB-SN connection through detecting GRBs that were not initially collimated towards us.

Commensal observations in deep fields, such as the LADUMA, MHONGOOSE and Fornax fields, will allow the detection of a more complete sample of radio events, possibly including highly obscured ones, and better establish the population ratios. Tying down the flux and spectrum of GRBs and SNe in the MeerKAT radio bands will allow us to determine the complete physical parameters of the explosion, which has only been possible for a few out of many hundreds of GRBs with afterglows so far. Once we can compare the behaviour in the L band with possible other bands of MeerKAT, this will become all the more powerful.

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2.3.2 Core collapse supernovae

Many CCSNe are not observed at radio wavelengths or, if observed, only followed at radio if there is a detection early after its explosion or optical detection (a few days to a few weeks). The sensitivity of MeerKAT will allow us to follow a statistically meaningful number of exploding CCSNe per year within 40 Mpc with a modest amount of MeerKAT time, permitting us to also obtain the radio luminosity function of CCSNe. Some individual CCSNe result in unique views of the final decades of evolution of the most massive stars (e.g. SN2014C, right panel of Fig 2).

The ideal cadence for the commensal detections of CCSNe is that the same fields are visited 3-5 times per year (LADUMA, MHONGOOSE). Assuming a maximum effective distance of 150 Mpc to discover CCSNe, we estimate that ThunderKAT could yield between 20 and 50 blind CCSNe discoveries, every year.

2.3.3 Type Ia supernovae with MeerKAT

Type Ia SNe, the end-products of white dwarfs, have been used to make the essential discovery of the accelerating expansion of the universe, yet we do not know what their progenitors are: a C+O white dwarf and a non-degenerate star (single-degenerate scenario), or two white dwarfs (double-degenerate scenario). Radio observations can discriminate between the progenitor models of SNe Ia. For example, in all scenarios with mass transfer from a companion, a significant amount of circumstellar gas is expected, and therefore a shock is bound to form when the supernova ejecta are expelled. The situation would then be very similar to circumstellar interaction in core-collapse SNe (see Sect. 2.3.1), where the interaction of the blast wave from the supernova with its circumstellar medium results in strong radio and X-ray emission. On the other hand, the double-degenerate scenario will not give rise to any circumstellar medium close to the progenitor system, and hence essentially no prompt radio emission is expected.

We aim to perform deep ToO observations of up to two nearby (D < 20 Mpc) Type Ia SNe per year with ThunderKAT, aimed at making the first ever discovery of radio emission from a Type Ia SN (the estimated rate for SN Ia within this volume is 1 ± 1 per year). We remark that a detection would represent a breakthrough in our understanding of Type Ia SN progenitors, given the existing contraints on SN2011fe [17] and on SN2014J [18], and would validate the single-degenerate scenario. On the other hand, systematic non-detections will be so constraining that it will rule out essentially most, or all, single-degenerate scenarios, leaving the double-degenerate scenario as the only viable one.

We need the observations to be scheduled as soon as the SN candidate is confirmed as a type Ia SN, and to be done at the highest available frequency of the array, aiming at a rms of around or better than 1 μJy/beam.

2.4 Fast and coherent transients

2.4.1 Fast radio bursts

The nature of Fast Radio Bursts (FRBs) remains uncertain, and the largest fraction of these discovered and studied with MeerKAT are going to be done so via the TRAPUM/MeerTRAP projects. Nevertheless, for a telescope as sensitive as MeerKAT, it is entirely possible to discover a very bright FRB in our commensal short timescale imaging, and we anticipate finding and localising a

significant number of FRBs this way via our commensal observations. Fast imaging of observations commensal with TRAPUM will be a joint TRAPUM-ThunderKAT collaboration.

However, as well as the short coherent burst there remains the possibility that there is a synchrotron afterglow of the event [19], and subsequent literature, and/or that some events repeat [20] and may be associated with faint continuous sources.

2.5 Gravitational wave sources

2.5.1 Gravitational wave events and electro-magnetic counterparts

The recent direct detections of gravitational waves (GWs) from extragalactic binary black hole mergers by the advanced LIGO (aLIGO) detector has opened a new window into the Universe [21]. This discovery, together with the expected increase in the aLIGO sensitivity, and the addition of VIRGO detectors, suggests that the coming years will see many compact binary star mergers. The current localization of these GW sources is several hundred square degrees (90% containment probability), but this will likely improve to 300 deg^2 and 100 deg^2 by 2018 and by 2022, respectively. Finding the electromagnetic (EM) counterparts of GW sources is crucial for increasing the science yield from the aLIGO/VIRGO detections, such as 1) lifting degeneracies associated with the binary parameters inferred from the GW signal, 2) reducing the SNR for a significant GW detection by aLIGO/VIRGO, and 3) providing arcsec localization and identifying the precise merger redshift, thus setting/testing the energy and distance scales.

Compact binary mergers containing neutron stars, i.e. NS-NS/NS-BH systems, are expected to produce EM counterparts. With MeerKAT, the goal will be to study the radio afterglows, which probe the post-merger outflows and the (shocked) circum-merger environments. These afterglows are expected to be weak, 10s to 100s of μJy, and expected to peak on weeks – months timescales after the merger and detection of the GW signal. Although faint, such afterglows will probably be the only means of finding the EM counterparts of mergers located in dusty galaxies, where the optical kilonova could be highly extincted. With MeerLICHT, we will hunt for the blue (red) kilonova signature that is expected on day (week) timescales. We envisage the MeerKAT follow up observations to be carried out in four epochs logarithmically spaced between 1 day and 1 year post-merger. Subsequent monitoring/follow up will be necessary only for the radio transients identified in these epochs.

3. Commensal transient searches

In parallel with the targetted programmes outlined above, we will search all incoming data streams in the image plane for transients. We will aim to do this on timescales from ~ 1 sec upwards, at approximately logarithmic time intervals. For example, for a 'typical' 4hr observation we may search for transients at timescales of 1, 10, 100 and 1000 seconds. These searches will be carried out in near real time and will probably operate alongside the beam-formed transient searches associated with the TRAPUM and MeerTRAP projects.

By 'piggybacking' on the other approved LSP surveys, from wide to very deep fields, we will perform the most extensive blind image-plane radio search for transients ever undertaken. In some of our core areas, e.g. SNe, we can confidently predict that the commensal results will augment the

science, but the true value of the integrated commensal survey lies in providing a comprehensive understanding of the radio sky variability at all timescales and flux levels. We note that for L-band and lower frequency observations of transients it would be our intention to search for (inter)galactic HI absorption features.

We would like to stress that this aspect of the programme is important in that it is the major 'exploration of the unknown' aspect of the MeerKAT LSP, and a very important preparatory study for the SKA. However, the clearer knowledge we have gathered over the past half a decade shows that it is with targetted programmes such as those we have outlined above, that we will get the guaranteed high-profile science.

4. Comments on observing strategy

Within the ThunderKAT programme, we will need to use a range of different observing modes, including different speeds of ToO (in terms of response time) interleaved with regular observations (some of which may be regular monitoring of a significant number of point sources).

4.1 Commensality with other Large Survey Projects

Following the original MeerKAT LSP awards, we agreed with the other LSPs that we could search their data commensally for transients (with some appropriate 'reward' in terms of authorship). For the revised 2016 LSP plans we note:

- MeerTIME / TRAPUM / MeerGAL - These projects will search extensively in the galactic plane and globular clusters, which is good for us for searches for galactic transients;

- Fornax - This project will observe over two 4.5-hr epochs per pointing across the Fornax survey area;

- MHONGOOSE - This LSP will provide $6-8$ pointings per deep field, providing an excellent resource to look for faint (extragalactic) transients over time scales of weeks to months;

- LADUMA - This project provides the longest baseline for transient detections on a single pointing over time scales of weeks to months to years;

- MIGHTEE - We will provide a time-variable sky model to MIGHTEE.

4.2 MeerLICHT and the need for some night time observations

All of the ThunderKAT science benefits from having simultaneous optical data during the MeerKAT observations. For transients discovered in commensal searches, the simultaneous optical flux and radio flux density measurements of an astrophysical transient allow an initial classification (Stewart et al. 2016, in prep) which will assist in allocating and prioritising multi-wavelength follow-up resources. In this regard, ThunderKAT is already part of a consolidated multi-year South African-led program for rapid follow up of various classes of transients on the Southern African Large Telescope (SALT).

Acknowledgements

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