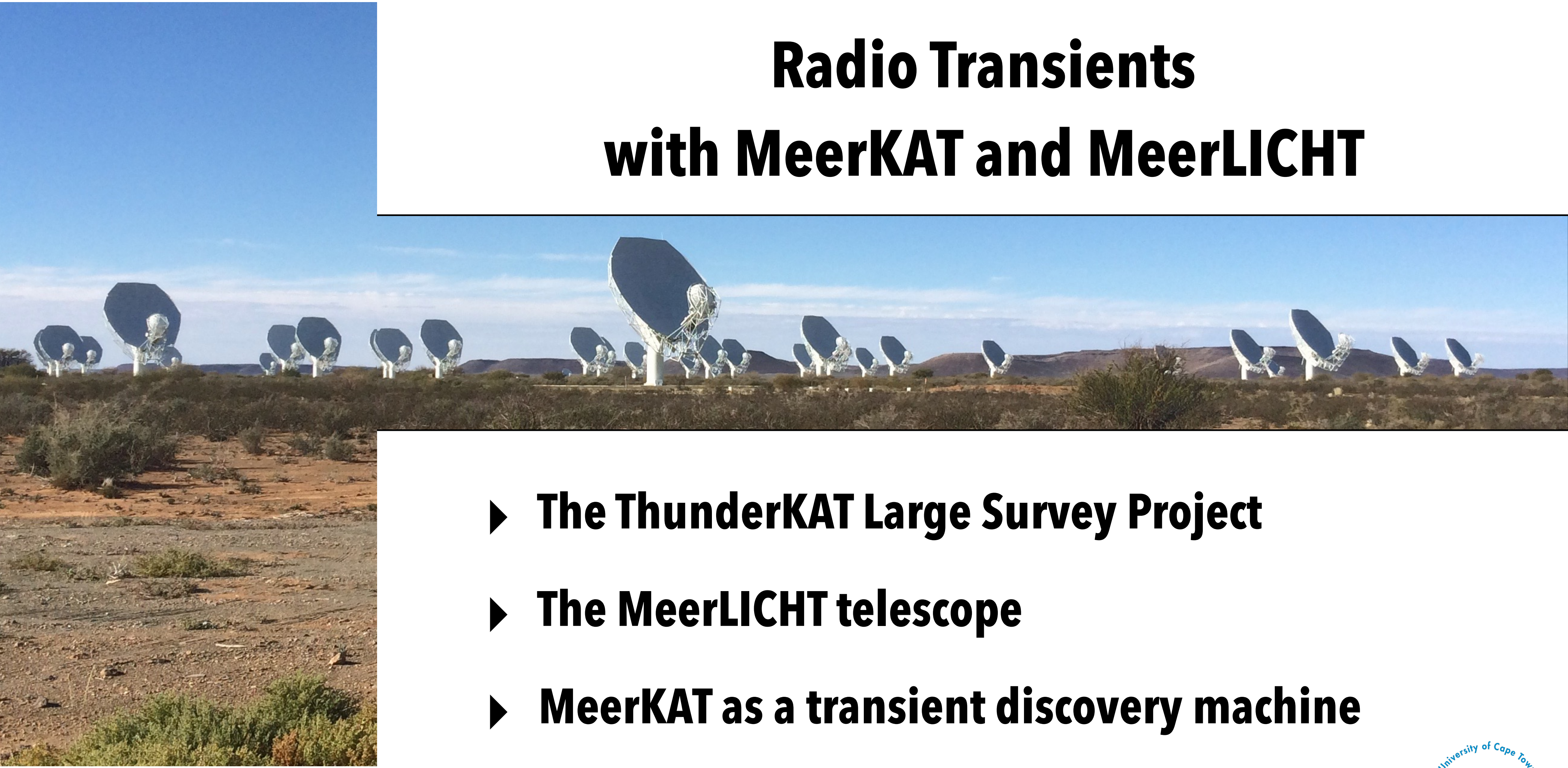
Radio Transients
with MeerKAT and MeerLICHT



- The ThunderKAT Large Survey Project
- The MeerLICHT telescope
- MeerKAT as a transient discovery machine

Patrick Woudt | Head of Department: Astronomy (University of Cape Town)

With thanks to: Rob Fender and Paul Groot
and the members of the ThunderKAT and MeerLICHT teams

H.E.S.S. 20th anniversary conference - 17 October 2022

MeerKAT and the SKA

MeerKAT

Technical specifications

- 64x 13.5-m Gregorian offset antennas distributed over an 8-km baseline
- Three GHz frequency receivers: **0.6 - 1.0 GHz** / **0.9 - 1.7 GHz** / 1.6 - 3.5 GHz
- Wide field of view: 1 square degree at 1.3 GHz and excellent instantaneous sensitivity

Pathway to the Square Kilometre Array

- MeerKAT was inaugurated on 13 July 2018 (SKA phase 0) - **MeerKAT science ongoing**
- To be extended by 16 SKA antennas [MeerKAT extended] - baselines up to 17 km
- To be incorporated in the SKA1-MID (SKA phase 1): ~200 antennas over a 150 km baseline
- SKA phase 2 extends on a continent wide scale

MeerKAT and the SKA

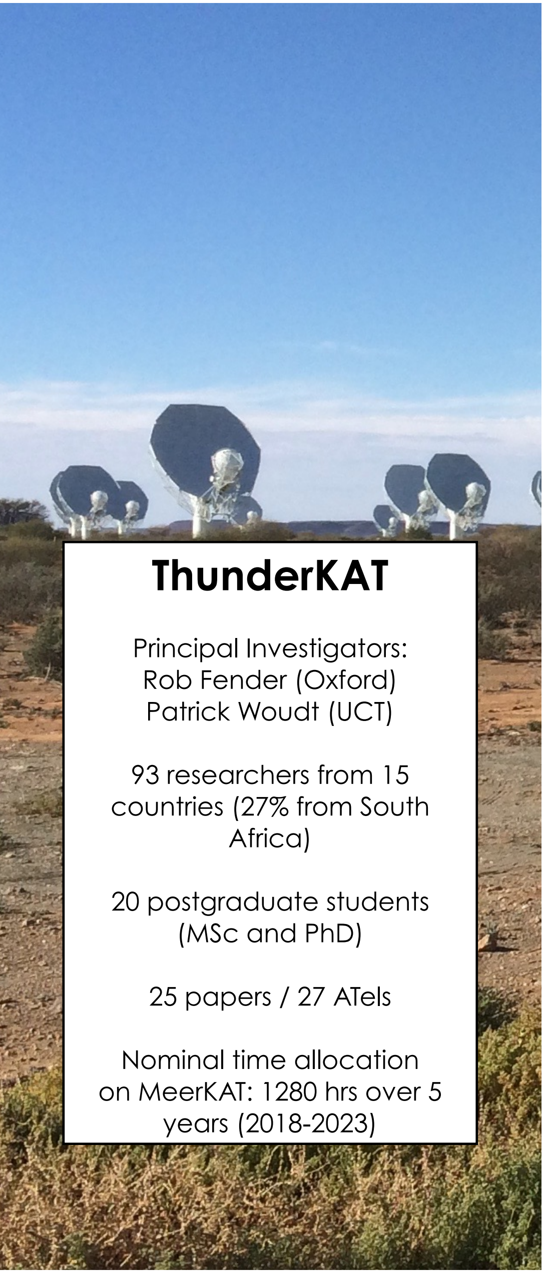
From MeerKAT to the Square Kilometre Array

Conversion of unused telecommunication dishes in Africa - first African VLBI Network (AVN) dish in Kutunse (Ghana).
Opened July 2017.

MeerKAT, core of SKA1-Mid in South Africa.

Opened July 2018.

Radio Transients and Variables with MeerKAT



ThunderKAT

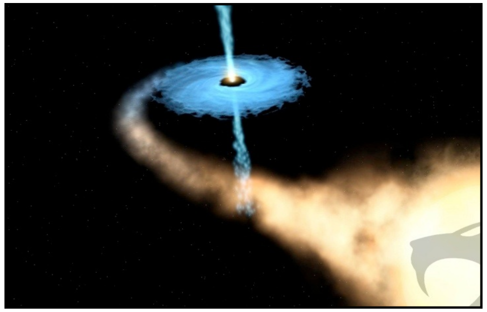
Principal Investigators:
Rob Fender (Oxford)
Patrick Woudt (UCT)

93 researchers from 15 countries (27% from South Africa)

20 postgraduate students (MSc and PhD)

25 papers / 27 ATels

Nominal time allocation on MeerKAT: 1280 hrs over 5 years (2018-2023)



ThunderKAT targeted observations of transients

- Cataclysmic Variables
- Short Gamma-Ray Bursts [**LIGO O4 starts 2023**]
- Type Ia Supernovae
- X-ray Binaries

ThunderKAT commensal observations of transients

- Image domain (> 2 sec): commensal imaging of all MeerKAT LSP data

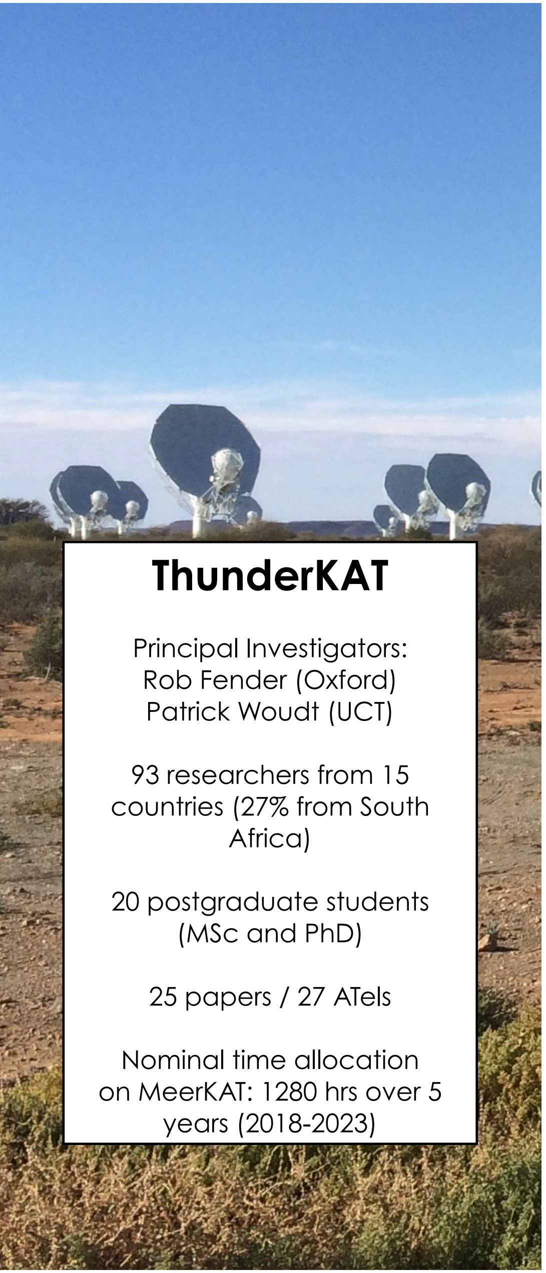
Other image domain transient observations with MeerKAT via Open Time and DDT:

- Tidal disruption events, very high energy (VHE) gamma-ray bursts, novae, etc.

Other commensal observations with MeerKAT of transients:

- Time domain (< 2 sec): MeerTRAP

active collaboration between **MeerTRAP** and **ThunderKAT** (imaging=localisation)



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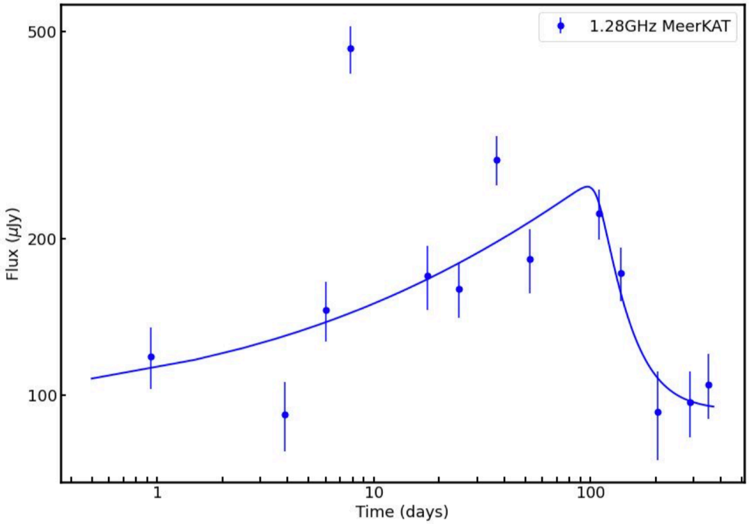
Radio Transients with MeerKAT (ThunderKAT)

Cosmic explosions

- short gamma-ray burst and nearby type Ia Supernovae



The VHE GRB190114C as observed by MeerKAT

Reikantseone Diretse, MSc student UCT (DDT and Open Time programme on MeerKAT)

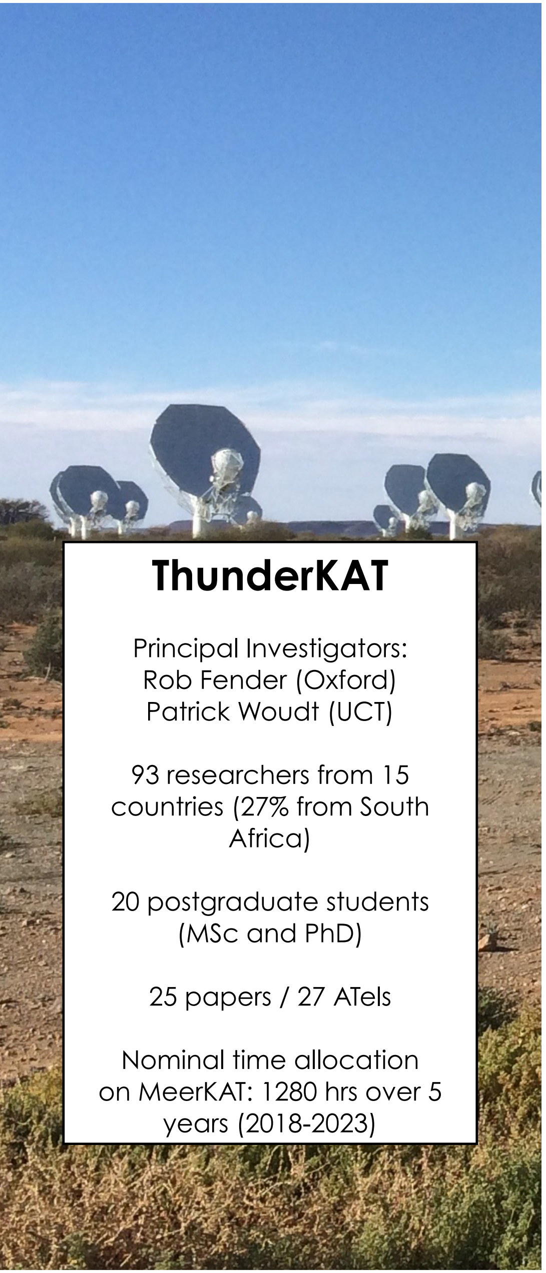
- Intrinsically faint (few 10s of microJy)
- nearby type Ia supernovae (< 20 Mpc)
- follow up gravitational wave alerts from binary neutron stars if short GRB is detected

Not included:

- long GRBs (Open Time or DDT)
- core collapse supernovae

LIGO/Virgo/KAGRA O4 starts in 2023

Radio Transients with MeerKAT (ThunderKAT)



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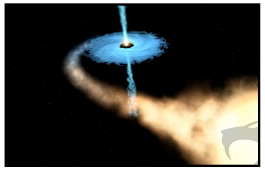
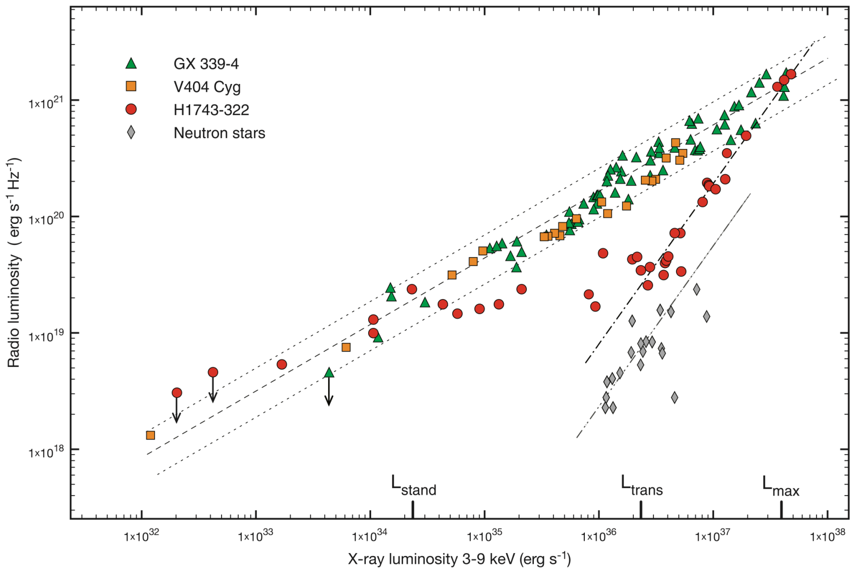
Black holes and neutron stars in X-ray binaries

- 1000+ observations of selected XRBs in outburst, quasi-simultaneous with X-ray observations



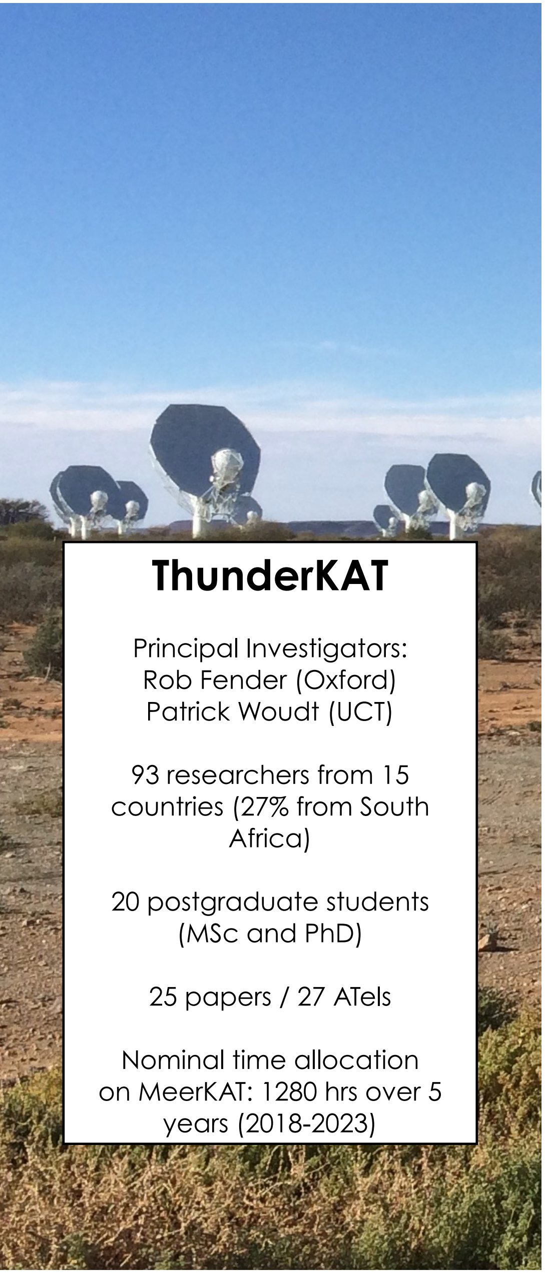


- weekly monitoring slot (1 hr/week)
- between 2 and 5 sources / week
- GX 339-4 every week (**unique dataset**)

Radiatively efficient accreting black holes in the hard state: the case study of H1743-322

Coriat, M. *et al.* MNRAS 414 (2011) 677-690

Radio Transients with MeerKAT (ThunderKAT)



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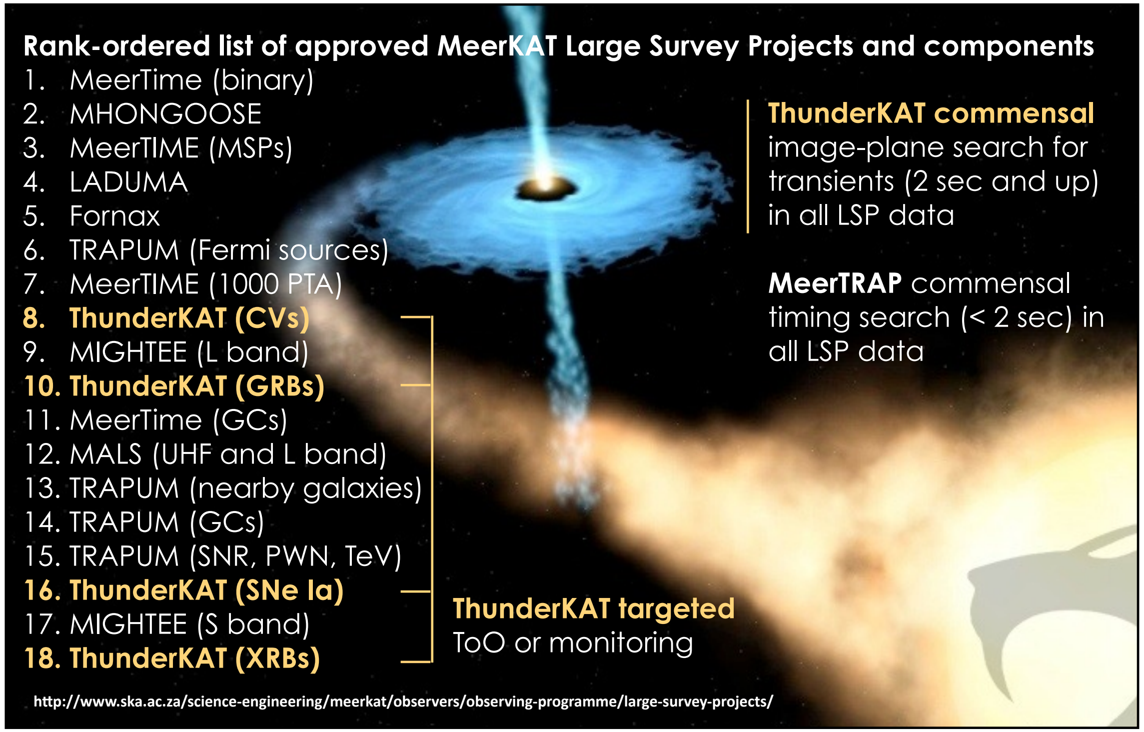
Radio transients and the exploration of the unknown [commensal with all MeerKAT LSPs]

- Any radio transient discovered in the commensal imaging of MeerKAT survey data



Rank-ordered list of approved MeerKAT Large Survey Projects and components

1. MeerTime (binary)
2. MHONGOOSE
3. MeerTIME (MSPs)
4. LADUMA
5. Fornax
6. TRAPUM (Fermi sources)
7. MeerTIME (1000 PTA)
8. **ThunderKAT (CVs)**
9. MIGHTEE (L band)
10. **ThunderKAT (GRBs)**
11. MeerTime (GCs)
12. MALS (UHF and L band)
13. TRAPUM (nearby galaxies)
14. TRAPUM (GCs)
15. TRAPUM (SNR, PWN, TeV)
16. **ThunderKAT (SNe Ia)**
17. MIGHTEE (S band)
18. **ThunderKAT (XRBs)**

ThunderKAT commensal image-plane search for transients (2 sec and up) in all LSP data

MeerTRAP commensal timing search (< 2 sec) in all LSP data

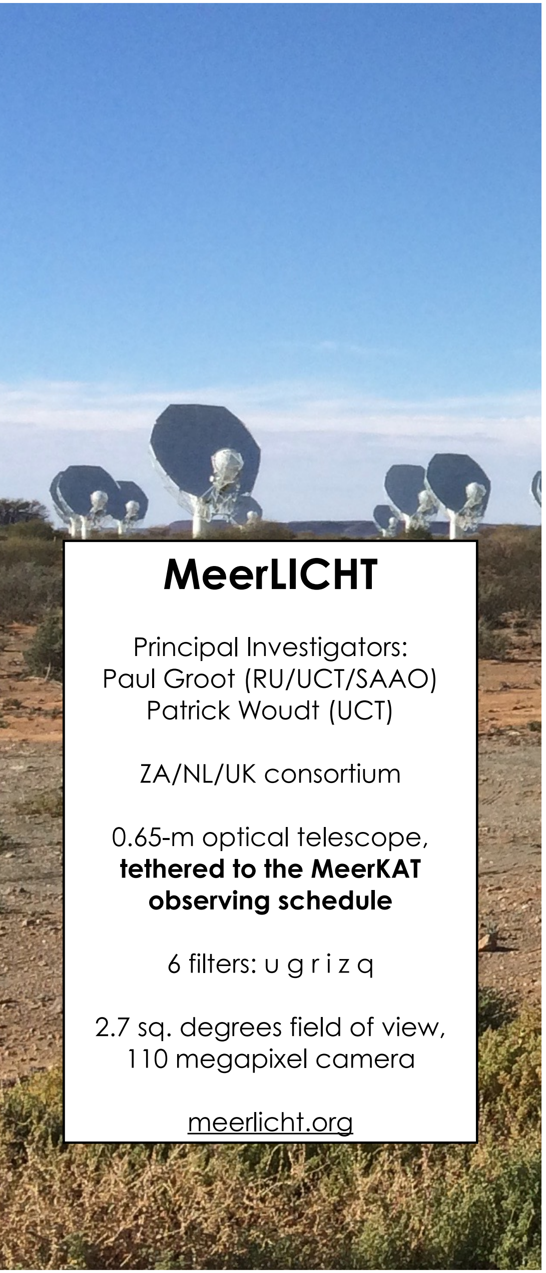
ThunderKAT targeted ToO or monitoring

http://www.ska.ac.za/science-engineering/meerkat/observers/observing-programme/large-survey-projects/

The different depths and cadences of these MeerKAT LSPs allow for an excellent coverage of transient phase-space.

MeerKAT as a radio transient discovery machine.

The MeerLICHT telescope



MeerLICHT

Principal Investigators:
Paul Groot (RU/UCT/SAAO)
Patrick Woudt (UCT)

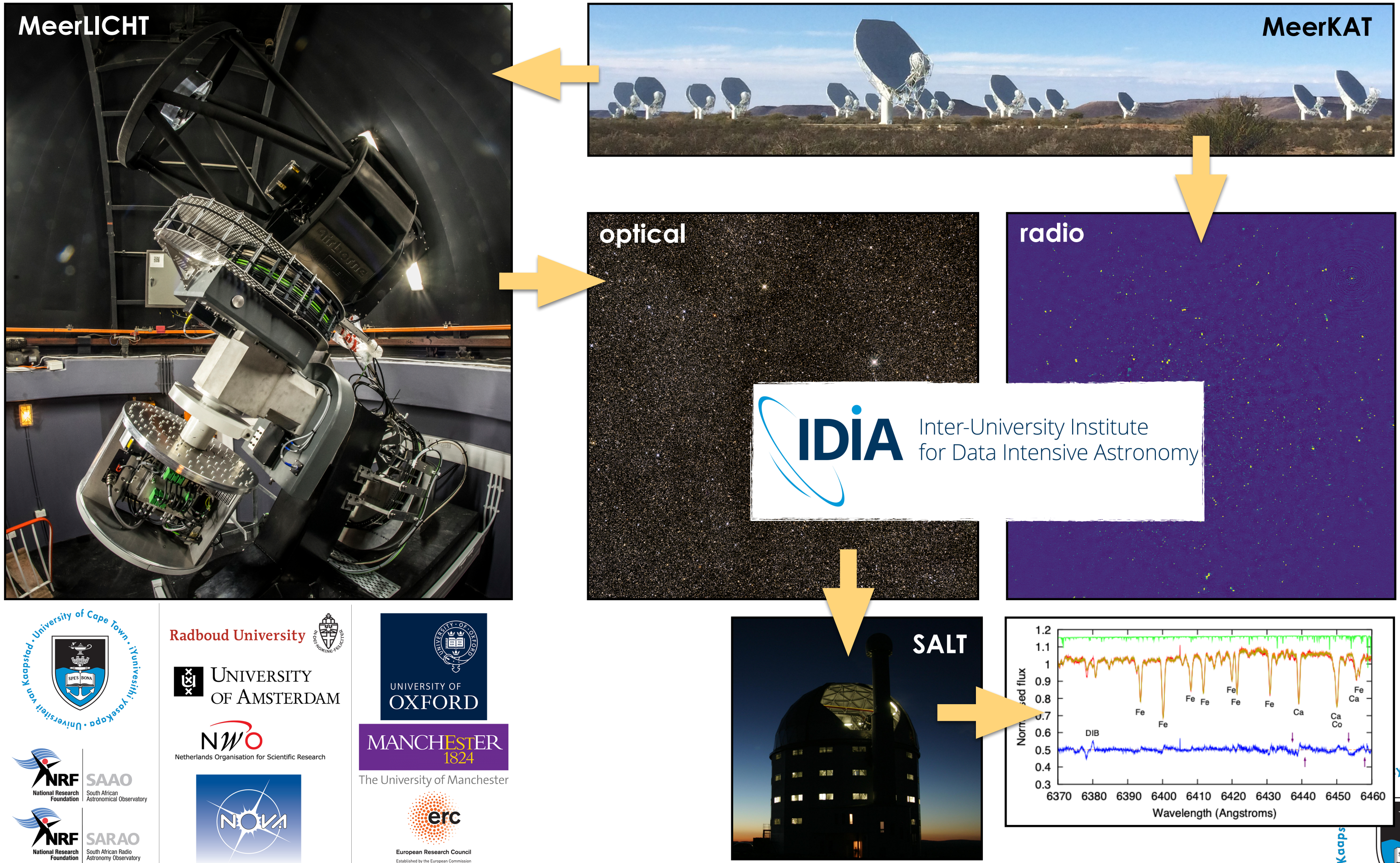
ZA/NL/UK consortium

0.65-m optical telescope,
tethered to the MeerKAT observing schedule

6 filters: u g r i z q

2.7 sq. degrees field of view,
110 megapixel camera

meerlicht.org



IDIA Inter-University Institute for Data Intensive Astronomy

University of Cape Town · iYunivesithi yaseKapa · Universiteit van Kaapstad

Radboud University

University of Amsterdam

NWO Netherlands Organisation for Scientific Research

University of Oxford

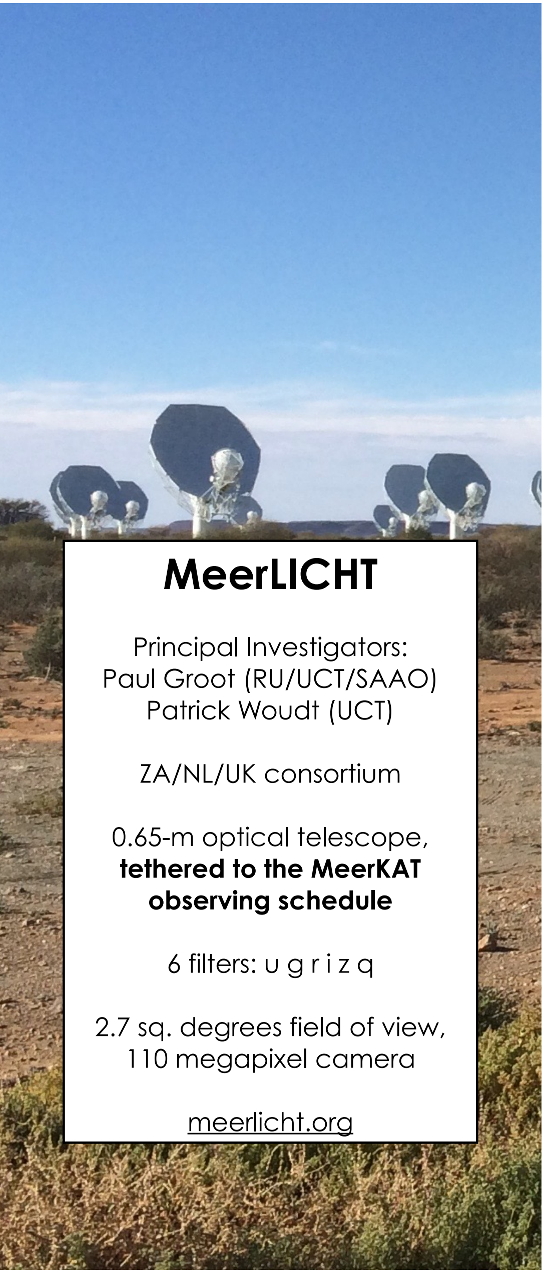
Manchester 1824 The University of Manchester

NRF National Research Foundation SAAO South African Astronomical Observatory

NRF National Research Foundation SARAO South African Radio Astronomy Observatory

NOVA

erc European Research Council



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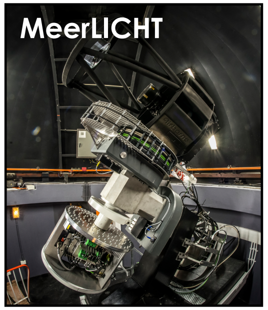
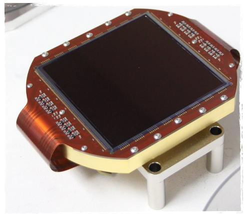


MeerLICHT operational details

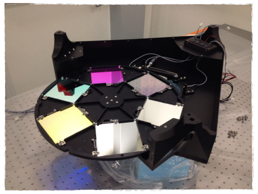
- located at the Sutherland station of SAAO (co-located with SALT)
- fully robotic
- science operations since June 2019
- automated link with MeerKAT since October 2020

MeerLICHT technical details

- 110 megapixel STA camera
- pixel size: 0.56"
- six filters: u g r i z q
- limiting magnitude q: ~20.7 mag (60 sec)
- prototype for the BlackGEM telescope array



STA chip (10.5k x 10.5k)

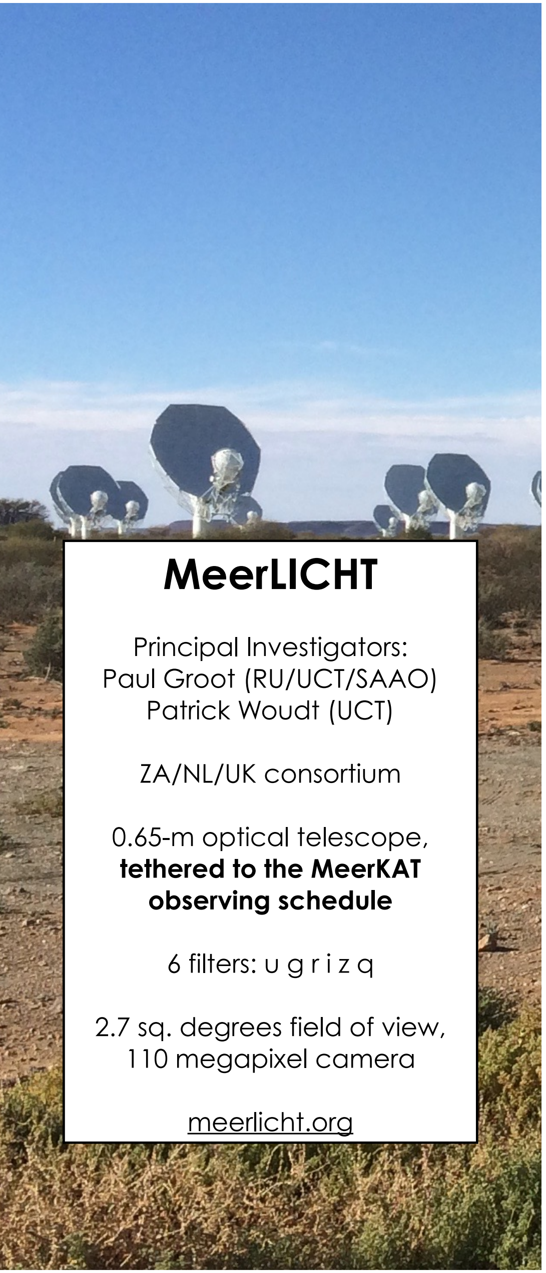


ugrizq filters

Filter	Wavelength range (A)
u	3500-4100
g	4100-5500
q	4400-7200
r	5630-6900
i	6900-8400
z	8400-9900

MeerKAT data processing details

- real-time processing pipeline (BlackBOX) at **IDIA**
- full source catalogue
- transient source catalogue (ZOGY difference imaging)
- database accessible to consortium via web interface
- special thanks to Paul Vreeswijk (BlackBOX) and Bart Scheers (Database)



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6 filters: u g r i z q

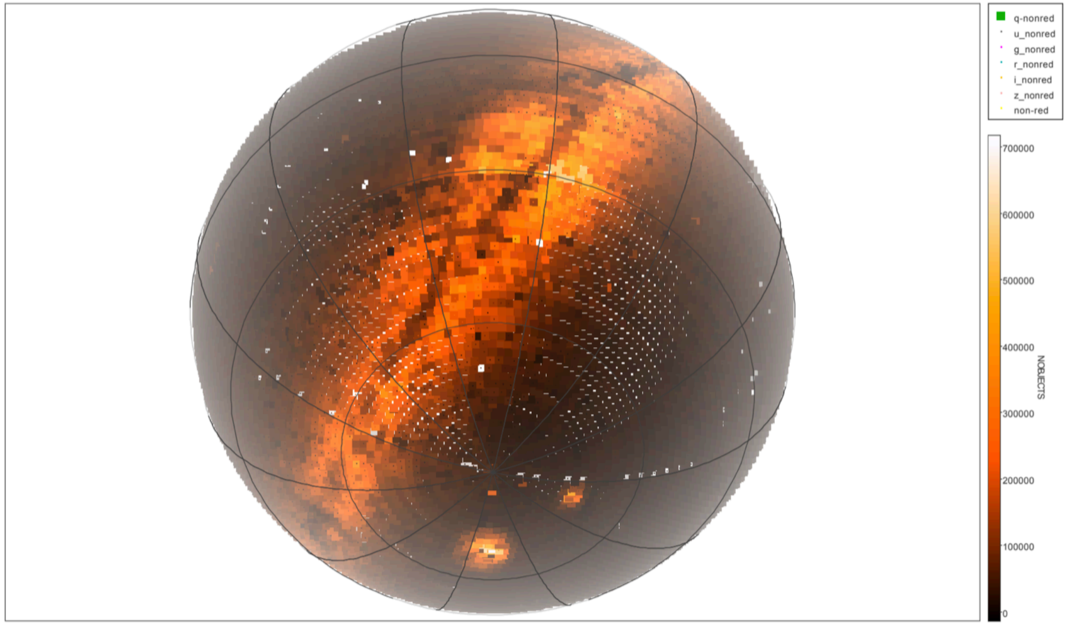
2.7 sq. degrees field of view,
110 megapixel camera

meerlicht.org

The MeerLICHT telescope

MeerLICHT scientific programme

- **primary objective: provide a simultaneous optical view of the MeerKAT transient radio sky**
  - in practise: co-observe (real-time) every MeerKAT LSP observation at night time
- complete southern sky survey (south of declination +30 deg, 12608 fields)
- twilight transient programme (nearby galaxies)



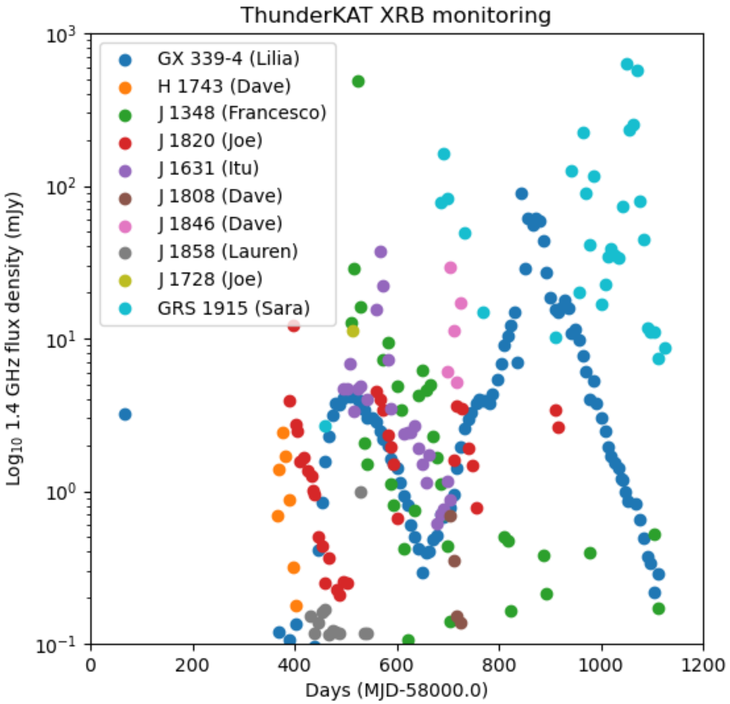
MeerLICHT sky distribution

- MeerLICHT q-band source density showing the near-complete coverage of the southern sky.
- Peak is at 700,000 sources per image, which translates to 260,000 sources per square degree

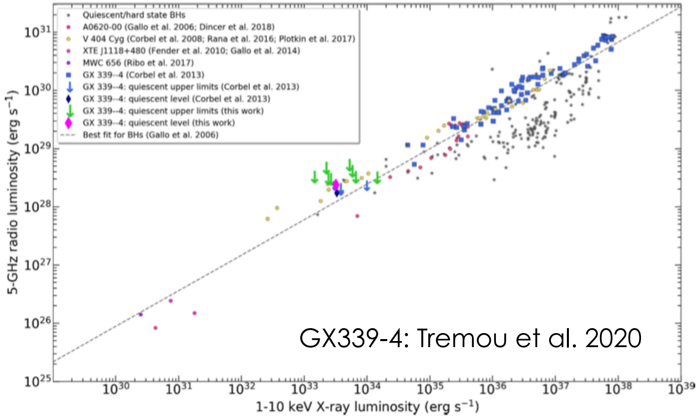
New Results from MeerKAT (XRBs)

Leads:
In general new XRBs in the programme are allocated to postgraduate students or emerging researchers

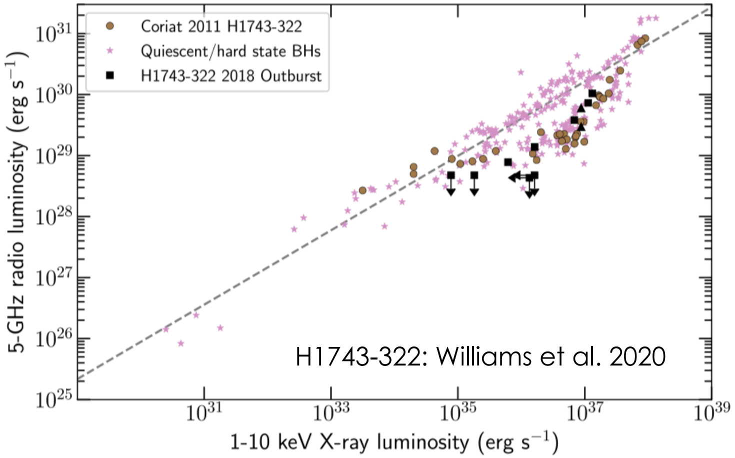
Status XRB programme on MeerKAT



ThunderKAT XRB weekly monitoring programme: status at end of September 2020 (end of year 2)
Picture: Rob Fender



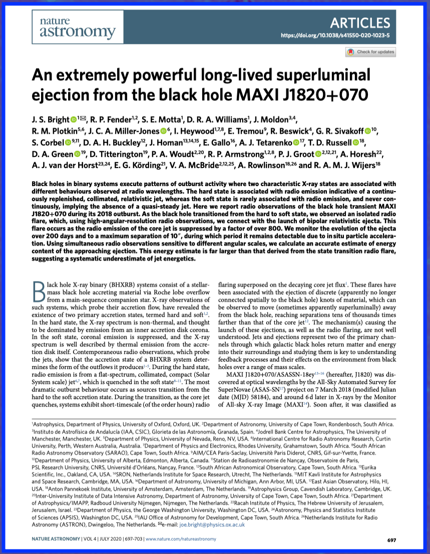
GX339-4: Tremou et al. 2020



H1743-322: Williams et al. 2020

New Results: ThunderKAT & MeerLICHT

Targeted observations ThunderKAT (XRBs)



nature astronomy

ARTICLES

https://doi.org/10.1038/s41550-020-1023-5

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An extremely powerful long-lived superluminal ejection from the black hole MAXI J1820+070

J. S. Bright[1]✉, R. P. Fender[1,2], S. E. Motta[1], D. R. A. Williams[1], J. Moldon[3,4], R. M. Plotkin[5,6], J. C. A. Miller-Jones[6], I. Heywood[1,7,8], E. Tremou[9], R. Beswick[4], G. R. Sivakoff[10], S. Corbel[9,11], D. A. H. Buckley[12], J. Homan[13,14,15], E. Gallo[16], A. J. Tetarenko[17], T. D. Russell[18], D. A. Green[19], D. Titterington[19], P. A. Woudt[2,20], R. P. Armstrong[1,2,8], P. J. Groot[2,12,21], A. Horesh[22], A. J. van der Horst[23,24], E. G. Körding[21], V. A. McBride[2,12,25], A. Rowlinson[18,26] and R. A. M. J. Wijers[18]

Black holes in binary systems execute patterns of outburst activity where two characteristic X-ray states are associated with different behaviours observed at radio wavelengths. The hard state is associated with radio emission indicative of a continuously replenished, collimated, relativistic jet, whereas the soft state is rarely associated with radio emission, and never continuously, implying the absence of a quasi-steady jet. Here we report radio observations of the black hole transient MAXI J1820+070 during its 2018 outburst. As the black hole transitioned from the hard to soft state, we observed an isolated radio flare, which, using high-angular-resolution radio observations, we connect with the launch of bipolar relativistic ejecta. This flare occurs as the radio emission of the core jet is suppressed by a factor of over 800. We monitor the evolution of the ejecta over 200 days and to a maximum separation of 10″, during which period it remains detectable due to in situ particle acceleration. Using simultaneous radio observations sensitive to different angular scales, we calculate an accurate estimate of energy content of the approaching ejection. This energy estimate is far larger than that derived from the state transition radio flare, suggesting a systematic underestimate of jet energetics.

Black hole X-ray binary (BHXRB) systems consist of a stellar-mass black hole accreting material via Roche lobe overflow from a main-sequence companion star. X-ray observations of such systems, which probe their accretion flow, have revealed the existence of two primary accretion states, termed hard and soft[1,2]. In the hard state, the X-ray spectrum is non-thermal, and thought to be dominated by emission from an inner accretion disk corona. In the soft state, coronal emission is suppressed, and the X-ray spectrum is well described by thermal emission from the accretion disk itself. Contemporaneous radio observations, which probe the jets, show that the accretion state of a BHXRB system determines the form of the outflows it produces[1–5]. During the hard state, radio emission is from a flat-spectrum, collimated, compact (Solar System scale) jet[6,7], which is quenched in the soft state[8–11]. The most dramatic outburst behaviour occurs as sources transition from the hard to the soft accretion state. During the transition, as the core jet quenches, systems exhibit short-timescale (of the order hours) radio flaring superposed on the decaying core jet flux[1]. These flares have been associated with the ejection of discrete (apparently no longer connected spatially to the black hole) knots of material, which can be observed to move (sometimes apparently superluminally) away from the black hole, reaching separations tens of thousands times farther than that of the core jet[12]. The mechanism(s) causing the launch of these ejections, as well as the radio flaring, are not well understood. Jets and ejections represent two of the primary channels through which galactic black holes return matter and energy into their surroundings and studying them is key to understanding feedback processes and their effects on the environment from black holes over a range of mass scales.

MAXI J1820+070/ASASSN-18ey[13–16] (hereafter, J1820) was discovered at optical wavelengths by the All-Sky Automated Survey for SuperNovae (ASAS-SN[17]) project on 7 March 2018 (modified Julian date (MJD) 58184), and around 6 d later in X-rays by the Monitor of All-sky X-ray Image (MAXI[14]). Soon after, it was classified as

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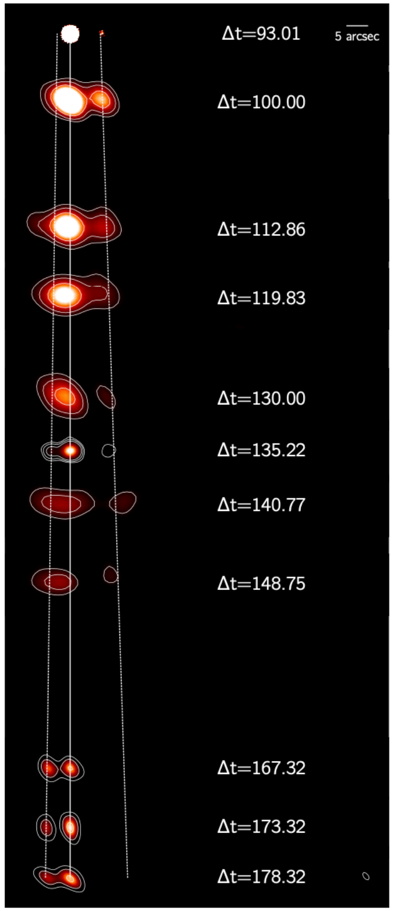
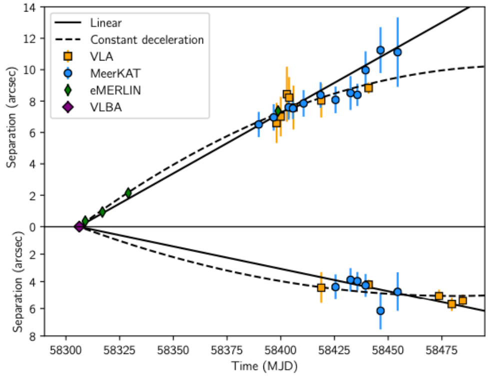
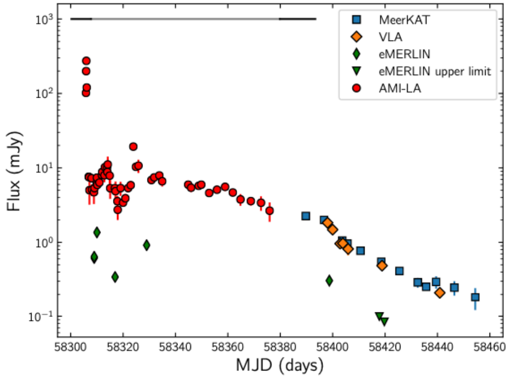
NATURE ASTRONOMY | VOL 4 | JULY 2020 | 697–703 | www.nature.com/natureastronomy 697

The black hole X-ray binary MAXI J1820+070







ThunderKAT targeted observations of X-ray Binaries

- A substantial number of XRBs show relativistic ejecta resolved at MeerKAT (angular) resolution
- Besides flux evolution, also capture proper motion of ejecta

An extremely powerful long-lived superluminal ejection from the black hole MAXI J1820+070

Bright, J.S., et *al.* Nature Ast 4 (2020) 697

Relativistic X-ray Jets from the Black Hole X-ray binary MAXI J1820+070

Espinasse, M., et *al.* Astrophysical Journal Letters 895 (2020) L31

New Results: ThunderKAT & MeerLICHT

Targeted observations ThunderKAT (XRBs)

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **493,** L132–L137 (2020) doi:10.1093/mnrasl/slaa019
Advance Access publication 2020 February 6

Radio and X-ray detections of GX 339–4 in quiescence using MeerKAT and *Swift*

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ABSTRACT

The radio–X-ray correlation that characterizes accreting black holes at all mass scales – from stellar mass black holes in binary systems to supermassive black holes powering active galactic nuclei – is one of the most important pieces of observational evidence supporting the existence of a connection between the accretion process and the generation of collimated outflows – or jets – in accreting systems. Although recent studies suggest that the correlation extends down to low luminosities, only a handful of stellar mass black holes have been clearly detected, and in general only upper limits (especially at radio wavelengths) can be obtained during quiescence. We recently obtained detections of the black hole X-ray binary (XRB) GX 339–4 in quiescence using the Meer Karoo Array Telescope (MeerKAT) radio telescope and *Swift* X-ray Telescope instrument on board the *Neil Gehrels Swift Observatory*, probing the lower end of the radio–X-ray correlation. We present the properties of accretion and of the connected generation of jets in the poorly studied low-accretion rate regime for this canonical black hole XRB system.

Key words: radio continuum: transients – X-rays: binaries.

1 INTRODUCTION

X-ray binaries (XRBs) are binary systems composed of a compact stellar remnant (a black hole or a neutron star) and a companion star with active mass accretion on to the stellar remnant. The presence of the collapsed star is revealed by X-ray and radio activity whose (relative and absolute) strength depends on the accretion rate on to the compact object and the state of the accretion disc that forms around the compact object. In low-mass XRBs, the accretion from a low-mass donor star occurs through Roche lobe overflow: matter streams from the companion star to the compact one, forming an accretion disc that redistributes angular momentum and emits copious radiation peaking in the X-rays.

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The black hole X-ray binary GX 339-4

Radio and X-ray detections of GX 339-4 in quiescence using MeerKAT and Swift

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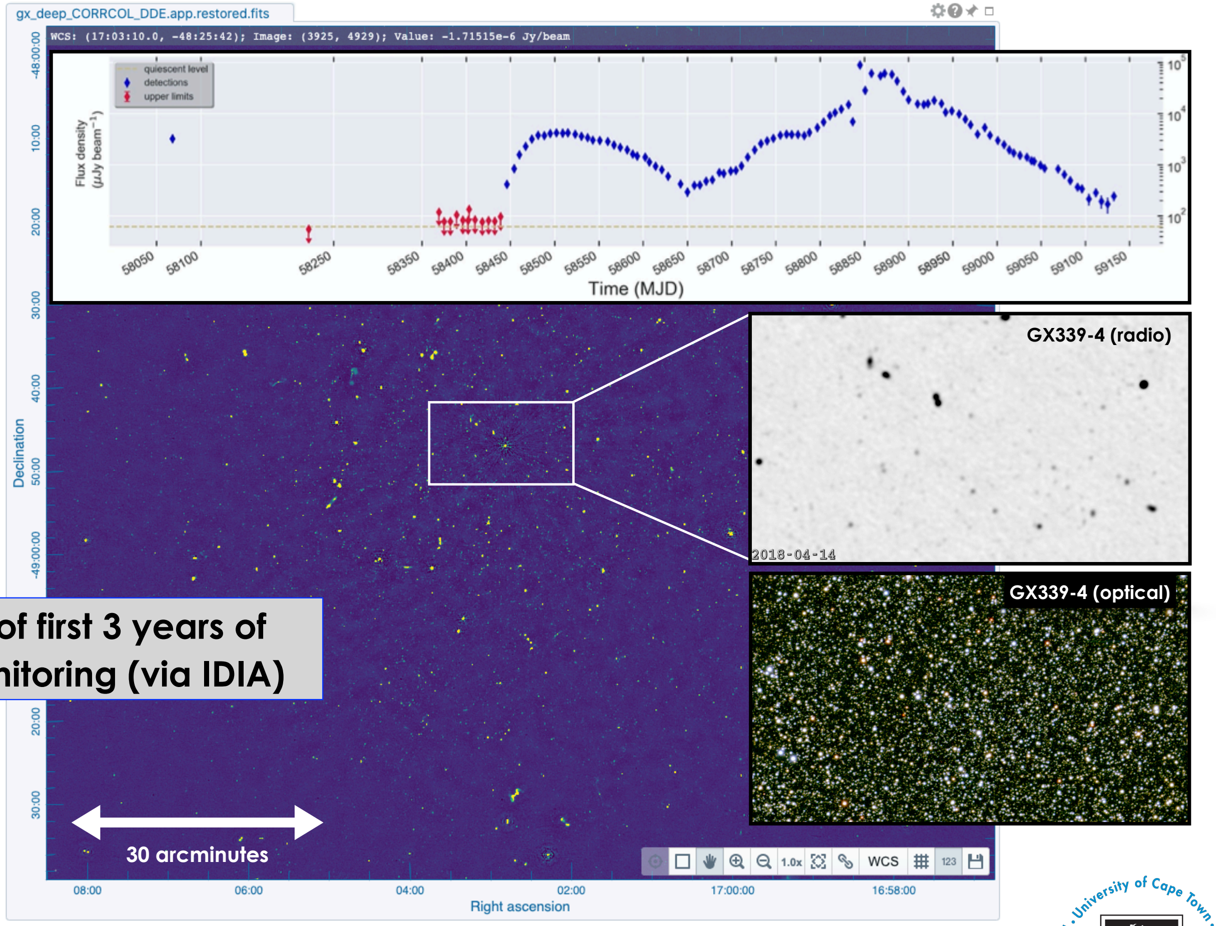

Public data release of first 3 years of GX 339-4 weekly monitoring (via IDIA)

New Results: ThunderKAT & MeerLICHT

Commensal observations ThunderKAT

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MKT J170456.2−482100: the first transient discovered by MeerKAT

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ABSTRACT

We report the discovery of the first transient with MeerKAT, MKT J170456.2−482100, discovered in ThunderKAT images of the low-mass X-ray binary GX339−4. MKT J170456.2−482100 is variable in the radio, reaching a maximum flux density of 0.71 ± 0.11 mJy on 2019 October 12, and is undetected in 15 out of 48 ThunderKAT epochs. MKT J170456.2−482100 is coincident with the chromospherically active K-type sub-giant TYC 8332-2529-1, and ∼ 18 yr of archival optical photometry of the star shows that it varies with a period of 21.25 ± 0.04 d. The shape and phase of the optical light curve changes over time, and we detect both X-ray and UV emission at the position of MKT J170456.2−482100, which may indicate that TYC 8332-2529-1 has large star spots. Spectroscopic analysis shows that TYC 8332-2529-1 is in a binary, and has a line-of-sight radial velocity amplitude of 43 km s^{-1}. We also observe a spectral feature in antiphase with the K-type sub-giant, with a line-of-sight radial velocity amplitude of ∼ 12 ± 10 km s^{-1}, whose origins cannot currently be explained. Further observations and investigation are required to determine the nature of the MKT J170456.2−482100 system.

Key words: stars: activity – binaries: spectroscopic – stars: flare – stars: peculiar.

1 INTRODUCTION

The radio sky contains many variable and transient sources, often found in follow-up observations of transients detected at other wavelengths such as optical, gamma-ray, and X-ray (e.g. Sood & Campbell-Wilson 1994; Zauderer et al. 2011; Chandra & Frail 2012; Horesh et al. 2013; Fong et al. 2015; Marsh et al. 2016; Hallinan et al. 2017; Bright et al. 2019). Blind searches for radio transients using interferometers present many challenges, particularly modest field of view (FoV) and limited observing cadence (e.g. Murphy et al. 2013; Mooley et al. 2016, 2018). With current wide FoV ($\gtrsim 1\,\mathrm{deg}^2$) instruments such as MeerKAT (Camilo et al. 2018), the Australian Square Kilometer Array Pathfinder (ASKAP; Johnston et al. 2008; Schinckel et al. 2012), APERTIF (Maan & van Leeuwen 2017), the LOw Frequency Array (LOFAR; van Haarlem et al. 2013), and the Murchison Wide Field Array (MWA; Tingay et al. 2012), surveying large areas of sky with various cadences and improved sensitivity is now possible. These new instruments could result in the discovery of tens to hundreds of transients (e.g. O'Brien et al. 2015).

Radio transients are commonly divided into two categories: coherent and incoherent (e.g. Pietka, Fender & Keane 2015); and both types of transient are investigated in the time domain with high-time resolution (milliseconds or less), and in image plane observations with a range of integration time-scales. In this publication we will focus on image plane searches. Current image plane transient searches include the Amsterdam-ASTRON Radio Transients Facility and Analysis Centre (AARTFAAC; Prasad et al. 2016; Kuiack et al. 2019), and the ASKAP Survey for Variables and Slow Transients (VAST; Murphy et al. 2013). Large surveys such as the Very Large Array (VLA) Sky Survey (VLASS; Lacy et al. 2019) are also being used to search for transients (Hallinan et al. 2013). It was originally theorized that image plane, low-frequency transient searches would detect many transient radio sources, but to date only one transient each has been found with LOFAR (Carbone et al. 2016; Stewart et al. 2016), the Long Wavelength Array (LWA; Varghese et al. 2019) and the MWA (Murphy et al. 2017), and no transients have been found with the VLA Low Band Ionospheric and Transient Experiment (VLITE; Polisensky et al. 2016). The rate of low-frequency Galactic transients may be higher, as inferred from the Galactic Center Radio Transients detected by VLA and Giant Metrewave Radio Telescope (GMRT; e.g. Hyman et al. 2005, 2009;

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The first radio transient discovered by MeerKAT

MKT J170456.2-482011: the first transient discovered by MeerKAT

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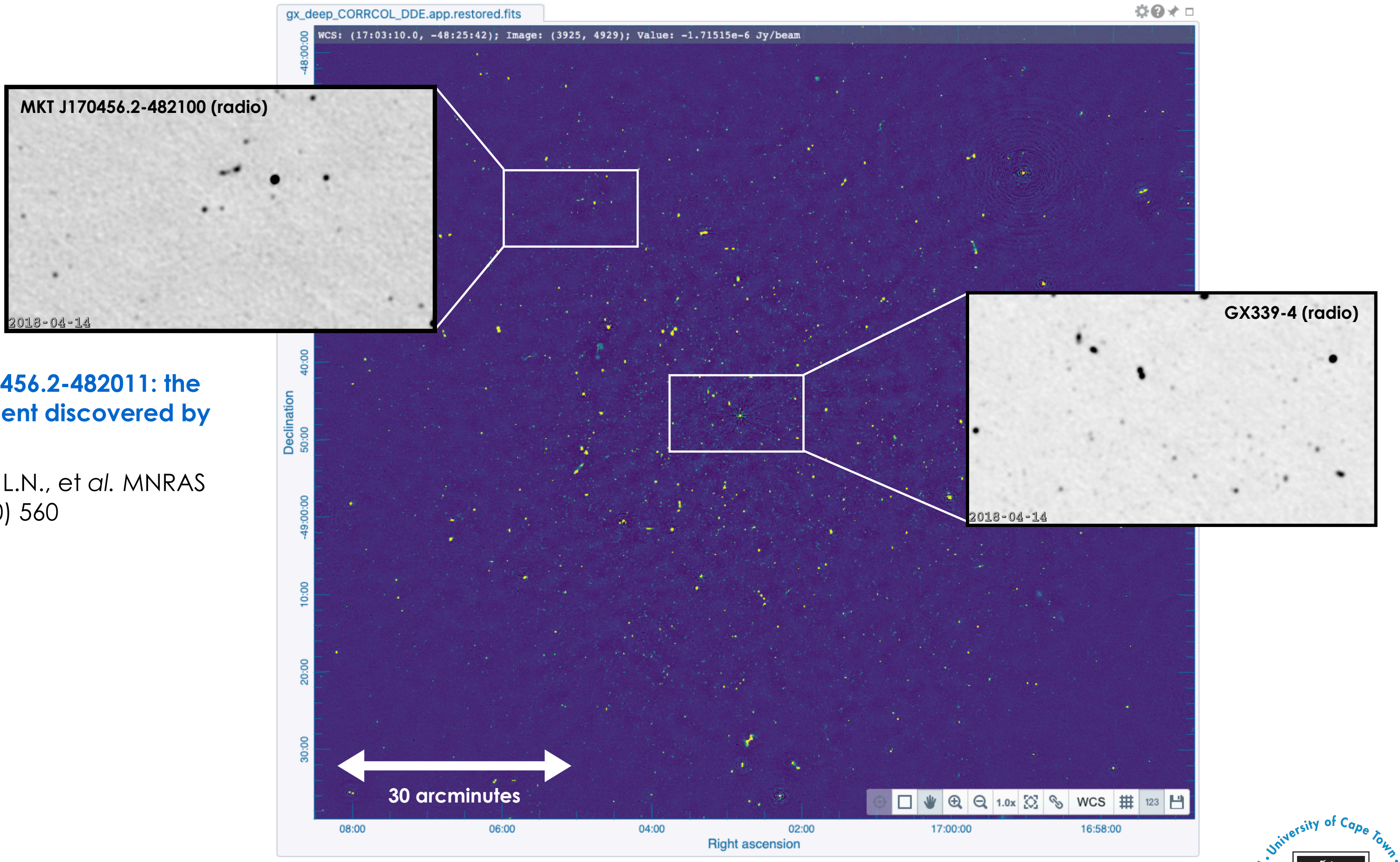

New Results:
ThunderKAT
& MeerLICHT

Commensal observations
ThunderKAT

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21 new long-term variables in the GX 339−4 field: two years of MeerKAT monitoring

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ABSTRACT
We present 21 new long-term variable radio sources found commensally in 2 yr of weekly MeerKAT monitoring of the low-mass X-ray binary GX 339−4. The new sources are vary on time-scales of weeks to months and have a variety of light-curve shapes and spectral index properties. Three of the new variable sources are coincident with multiwavelength counterparts; and one of these is coincident with an optical source in deep MeerLICHT images. For most sources, we cannot eliminate refractive scintillation of active galactic nuclei as the cause of the variability. These new variable sources represent 2.2 ± 0.5 per cent of the unresolved sources in the field, which is consistent with the 1–2 per cent variability found in past radio variability surveys. However, we expect to find short-term variable sources in the field and these 21 new long-term variable sources. We present the radio light curves and spectral index variability of the new variable sources, as well as the absolute astrometry and matches to coincident sources at other wavelengths.

Key words: radio continuum: galaxies – radio continuum: general.

1 INTRODUCTION

We are entering a new era of radio astronomy where we can execute untargeted, image-plane searches for variable and transient sources using sensitive instruments with wide field capabilities. Instruments such as the Australian Square Kilometre Array Pathfinder (ASKAP;[1] Hotan et al. 2021), the Karl G. Jansky Very Large Array (VLA; Perley et al. 2011), the Low Frequency Array (LOFAR; van Haarlem et al. 2013), the Murchison Wide Field Array (MWA; Tingay et al. 2012), and the (more) Karoo Array Telescope (MeerKAT; Camilo et al. 2018) are uncovering large samples of dynamic sources in the radio sky and facilitating their detailed light-curve analyses without the need for targeting each source individually.

Previous surveys and investigations of the changing radio sky in the image plane have revealed that ∼1–2 per cent of radio point sources at L-band (1.4 GHz) are variable (see e.g. Ofek et al. 2011, for a review).[2] Many of these past searches for variable sources used the VLA. For example, Carilli, Ivison & Frail (2003) searched the

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[1] https://www.atnf.csiro.au/projects/askap/index.html
[2] See http://www.tauceti.caltech.edu/kunal/radio-transient-surveys/index.html for an up-to-date list of untargeted radio surveys.

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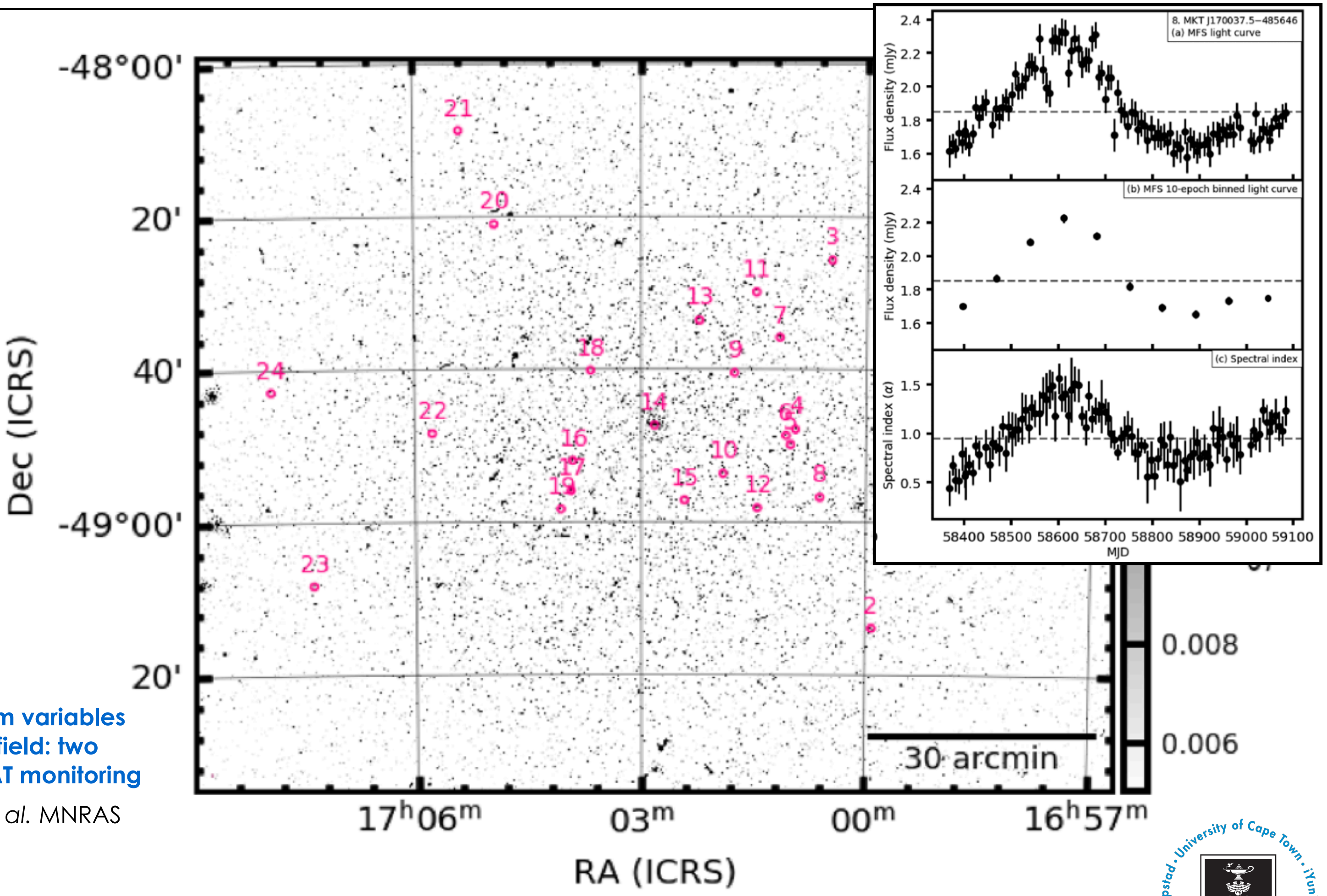
21 new long-term variables in the GX 339-4 field

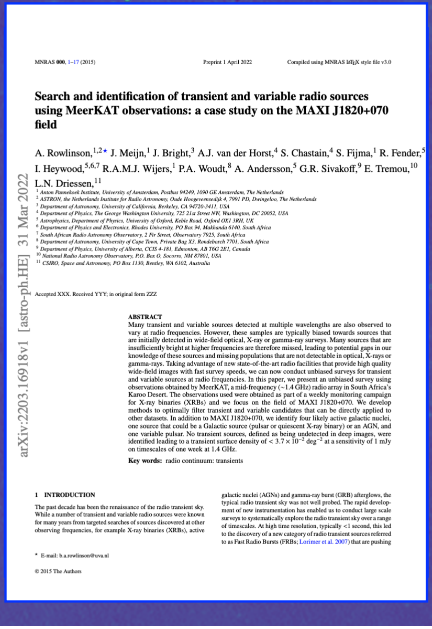


21 new long-term variables in the GX 339-4 field: two years of MeerKAT monitoring

Driessen, L.N., et *al.* MNRAS 512 (2022) 5037

New Results: ThunderKAT & MeerLICHT

Commensal observations ThunderKAT



MNRAS **000**, 1–17 (2015) Preprint 1 April 2022 Compiled using MNRAS LaTeX style file v3.0

arXiv:2203.16918v1 [astro-ph.HE] 31 Mar 2022

Search and identification of transient and variable radio sources using MeerKAT observations: a case study on the MAXI J1820+070 field

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
Many transient and variable sources detected at multiple wavelengths are also observed to vary at radio frequencies. However, these samples are typically biased towards sources that are initially detected in wide-field optical, X-ray or gamma-ray surveys. Many sources that are insufficiently bright at higher frequencies are therefore missed, leading to potential gaps in our knowledge of these sources and missing populations that are not detectable in optical, X-rays or gamma-rays. Taking advantage of new state-of-the-art radio facilities that provide high quality wide-field images with fast survey speeds, we can now conduct unbiased surveys for transient and variable sources at radio frequencies. In this paper, we present an unbiased survey using observations obtained by MeerKAT, a mid-frequency (~1.4 GHz) radio array in South Africa's Karoo Desert. The observations used were obtained as part of a weekly monitoring campaign for X-ray binaries (XRBs) and we focus on the field of MAXI J1820+070. We develop methods to optimally filter transient and variable candidates that can be directly applied to other datasets. In addition to MAXI J1820+070, we identify four likely active galactic nuclei, one source that could be a Galactic source (pulsar or quiescent X-ray binary) or an AGN, and one variable pulsar. No transient sources, defined as being undetected in deep images, were identified leading to a transient surface density of $< 3.7 \times 10^{-2}$ deg^{-2} at a sensitivity of 1 mJy on timescales of one week at 1.4 GHz.

Key words: radio continuum: transients

1 INTRODUCTION

The past decade has been the renaissance of the radio transient sky. While a number of transient and variable radio sources were known for many years from targeted searches of sources discovered at other observing frequencies, for example X-ray binaries (XRBs), active galactic nuclei (AGNs) and gamma-ray burst (GRB) afterglows, the typical radio transient sky was not well probed. The rapid development of new instrumentation has enabled us to conduct large scale surveys to systematically explore the radio transient sky over a range of timescales. At high time resolution, typically <1 second, this led to the discovery of a new category of radio transient sources referred to as Fast Radio Bursts (FRBs; Lorimer et al. 2007) that are pushing

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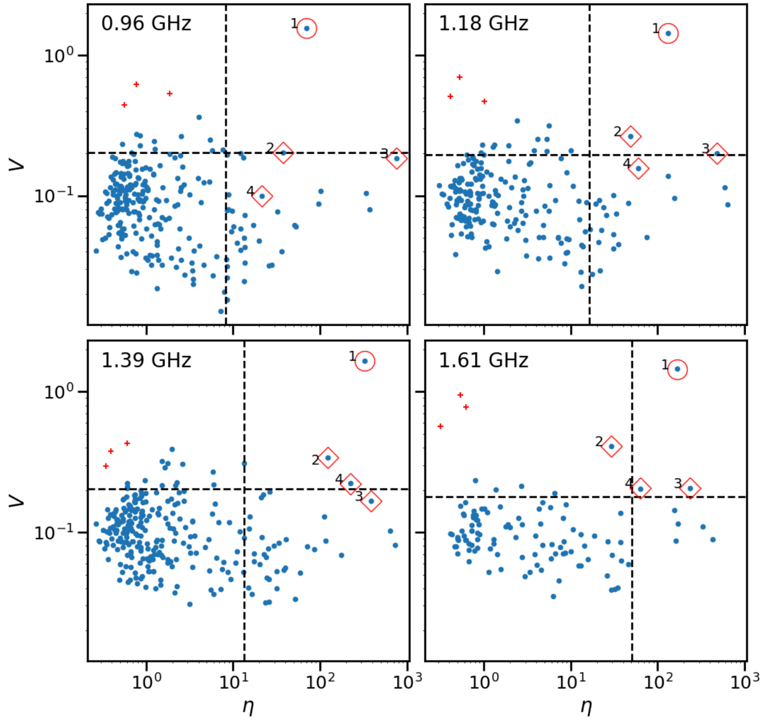
Variables and transients in the MAXI J1820 field

Search and identification of transient and variable sources using MeerKAT observations: a case study on the MAXI J1820+070 field

Rowlinson, A., et *al.* MNRAS submitted (2022) arXiv:2203.16918



Radio transient searches in commensal data

- Use **TrAP** (developed for LOFAR transient work)

Variability statistics:

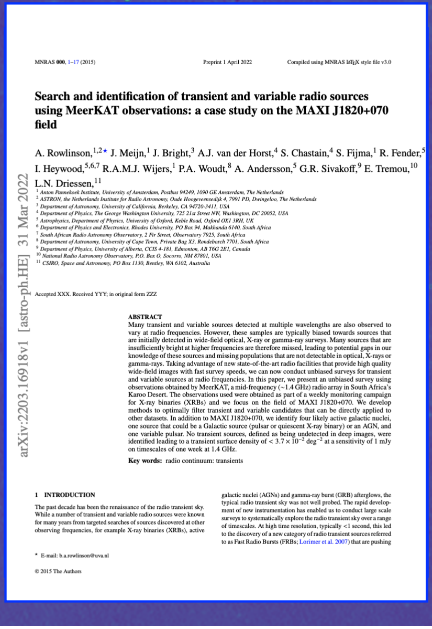
η : measure of the reduced chi-squared value when compared to a stable source.

V : modulation parameter, ratio of the sample standard deviation to the mean of its flux measurements

In general sources with large values of both V and η are likely to be identified as transients or variable.

New Results: ThunderKAT & MeerLICHT

Commensal observations ThunderKAT



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Variables and transients in the MAXI J1820 field

Search and identification of transient and variable sources using MeerKAT observations: a case study on the MAXI J1820+070 field

Rowlinson, A., et *al.* MNRAS in press (2022) arXiv:2203.16918

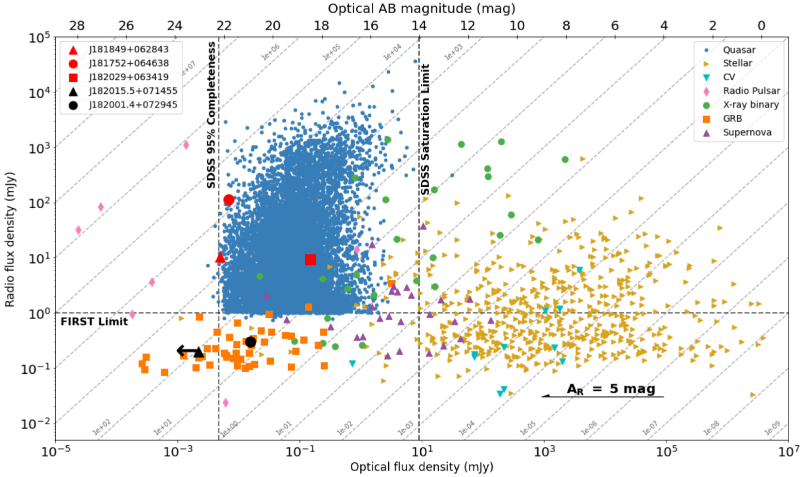
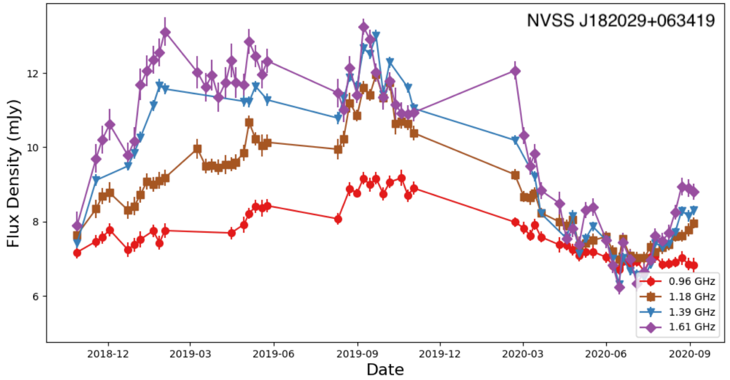


Figure 7. Radio flux density versus optical flux density for different populations of transient and variable sources, adapted from Figure 1 in Stewart et al. (2018). The two unidentified variable sources identified in Section 3.1 are shown with black symbols. The three variable sources identified in Section 3.2 are shown with red symbols and are consistent with quasars.



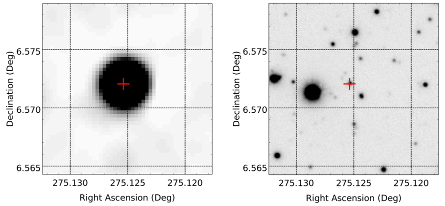
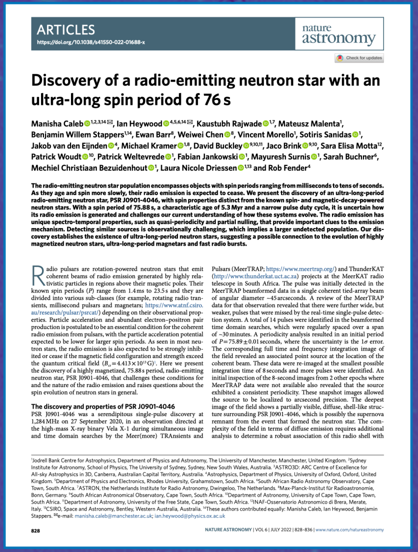


Figure C5. NVSS J182029+063419. Left: deep MeerKAT image. Right: PanSTARRS *z* band image. The red plus symbol shows the location of the source.

- Observing cadence set by ThunderKAT observations of MAXI J1820+070 (XRB)
- Frequency averaged into 4 bands (width: 215 MHz), see figure top-right
- spectral index at each epoch
- quasi-simultaneous **optical-radio** information allows initial classification (see figure top-left)

New Results:
ThunderKAT
& MeerLICHT

Commensal observations
MeerTRAP/ThunderKAT



ARTICLES
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Discovery of a radio-emitting neutron star with an ultra-long spin period of 76 s

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The radio-emitting neutron star population encompasses objects with spin periods ranging from milliseconds to tens of seconds. As they age and spin more slowly, their radio emission is expected to cease. We present the discovery of an ultra-long-period radio-emitting neutron star, PSR J0901-4046, with spin properties distinct from the known spin- and magnetic-decay-powered neutron stars. With a spin period of 75.88 s, a characteristic age of 5.3 Myr and a narrow pulse duty cycle, it is uncertain how its radio emission is generated and challenges our current understanding of how these systems evolve. The radio emission has unique spectro-temporal properties, such as quasi-periodicity and partial nulling, that provide important clues to the emission mechanism. Detecting similar sources is observationally challenging, which implies a larger undetected population. Our discovery establishes the existence of ultra-long-period neutron stars, suggesting a possible connection to the evolution of highly magnetized neutron stars, ultra-long-period magnetars and fast radio bursts.

Radio pulsars are rotation-powered neutron stars that emit coherent beams of radio emission generated by highly relativistic particles in regions above their magnetic poles. Their known spin periods (P) range from 1.4 ms to 23.5 s and they are divided into various sub-classes (for example, rotating radio transients, millisecond pulsars and magnetars; https://www.atnf.csiro.au/research/pulsar/psrcat/) depending on their observational properties. Particle acceleration and abundant electron–positron pair production is postulated to be an essential condition for the coherent radio emission from pulsars, with the particle acceleration potential expected to be lower for larger spin periods. As seen in most neutron stars, the radio emission is also expected to be strongly inhibited or cease if the magnetic field configuration and strength exceed the quantum critical field ($B_{cr} = 4.413 \times 10^{13}$ G)[1]. Here we present the discovery of a highly magnetized, 75.88 s period, radio-emitting neutron star, PSR J0901-4046, that challenges these conditions for and the nature of the radio emission and raises questions about the spin evolution of neutron stars in general.

The discovery and properties of PSR J0901-4046

PSR J0901-4046 was a serendipitous single-pulse discovery at 1,284 MHz on 27 September 2020, in an observation directed at the high-mass X-ray binary Vela X-1 during simultaneous image and time domain searches by the Meer(more) TRAnsients and Pulsars (MeerTRAP; https://www.meertrap.org/) and ThunderKAT (http://www.thunderkat.uct.ac.za) projects at the MeerKAT radio telescope in South Africa. The pulse was initially detected in the MeerTRAP beamformed data in a single coherent tied-array beam of angular diameter ~45 arcseconds. A review of the MeerTRAP data for that observation revealed that there were further wide, but weaker, pulses that were missed by the real-time single-pulse detection system. A total of 14 pulses were identified in the beamformed time domain searches, which were regularly spaced over a span of ~30 minutes. A periodicity analysis resulted in an initial period of $P = 75.89 \pm 0.01$ seconds, where the uncertainty is the 1σ error. The corresponding full time and frequency integration image of the field revealed an associated point source at the location of the coherent beam. These data were re-imaged at the smallest possible integration time of 8 seconds and more pulses were identified. An initial inspection of the 8-second images from 2 other epochs where MeerTRAP data were not available also revealed that the source exhibited a consistent periodicity. These snapshot images allowed the source to be localized to arcsecond precision. The deepest image of the field shows a partially visible, diffuse, shell-like structure surrounding PSR J0901-4046, which is possibly the supernova remnant from the event that formed the neutron star. The complexity of the field in terms of diffuse emission requires additional analysis to determine a robust association of this radio shell with

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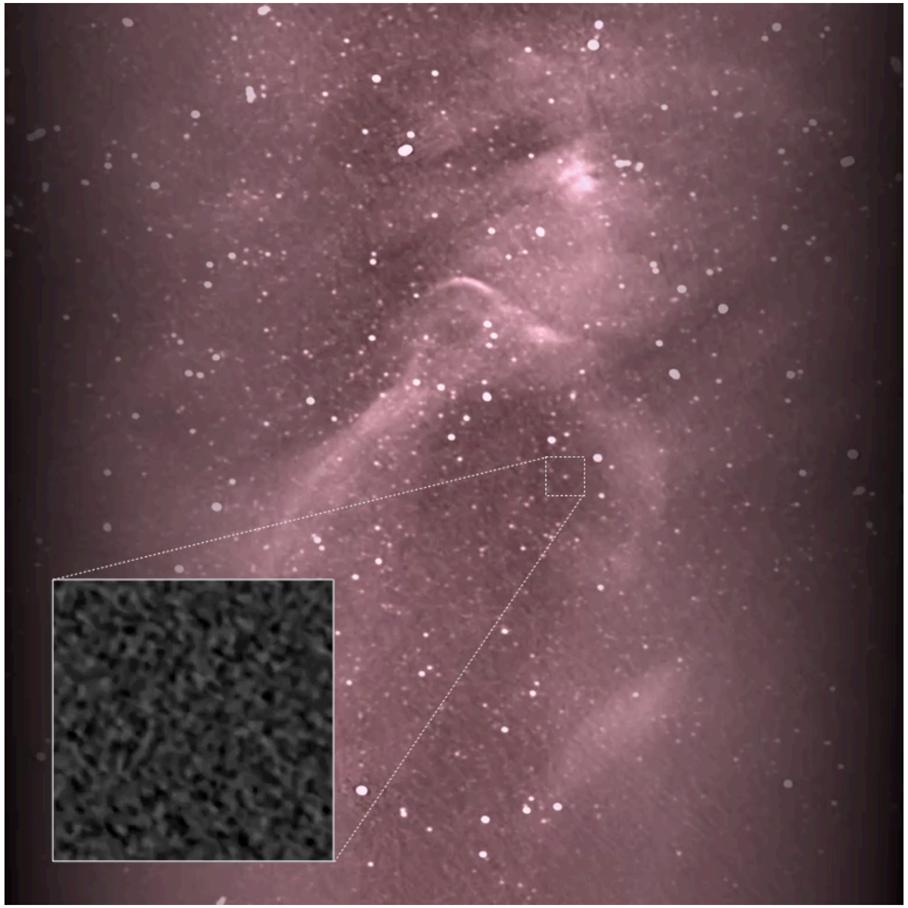
A 76-s pulsar discovered in the Vela X-1 field



MeerKAT discovery of radio emission from the Vela X-1 bow shock

van den Eijnden, J., et *al.* MNRAS (2022) 510, 515-530

- Only the second bow shock discovered at radio frequencies

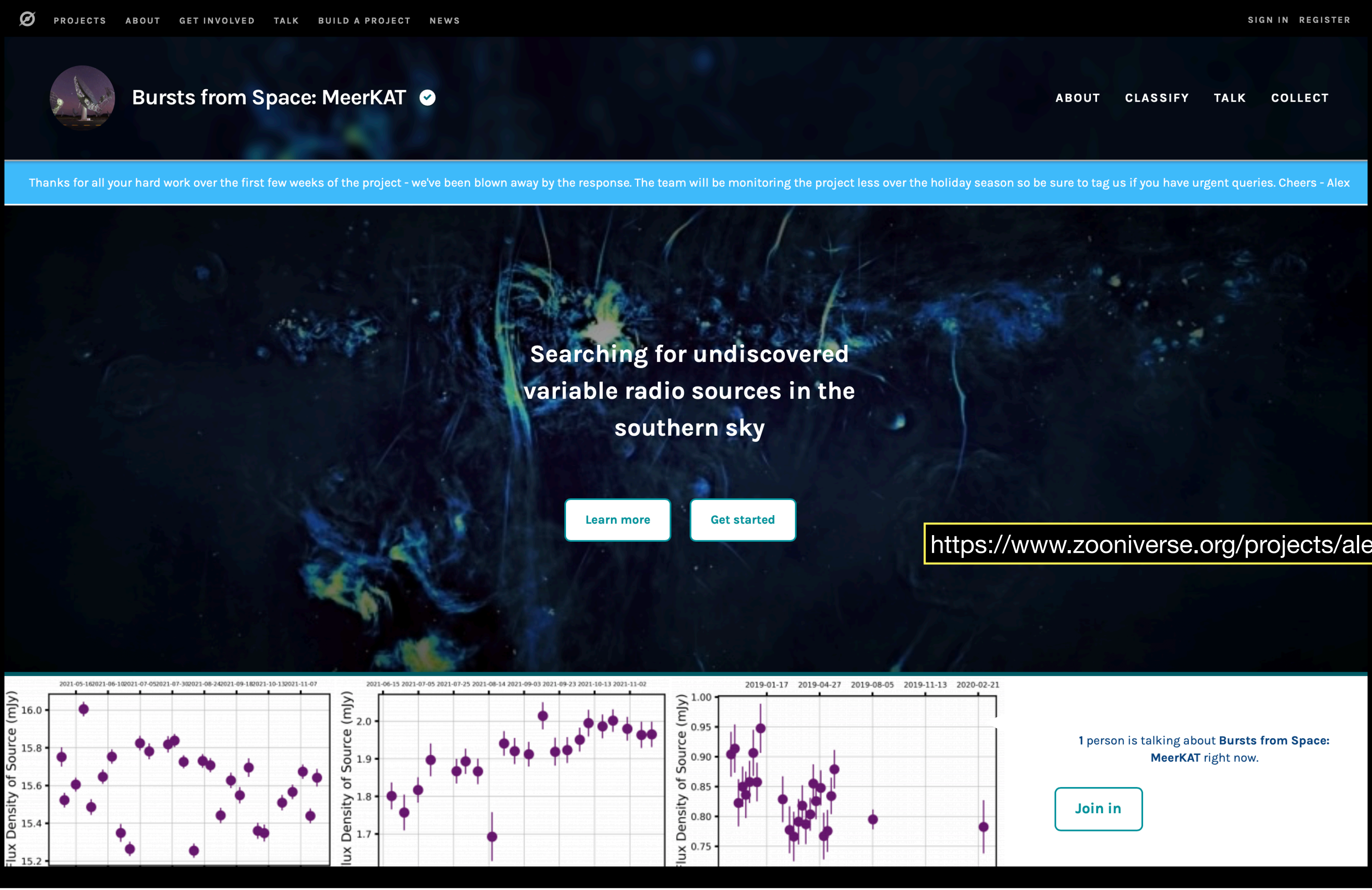
ThunderKAT commensal

- Discovery of a radio emitting neutron star with an ultra-long period of 76 seconds
- Synergy between **MeerTRAP** and **ThunderKAT**

Discovery of a radio-emitting neutron star with an ultra-long spin period of 76 s

Caleb, M., et *al.* Nature Astronomy (2022) 6, 828-836

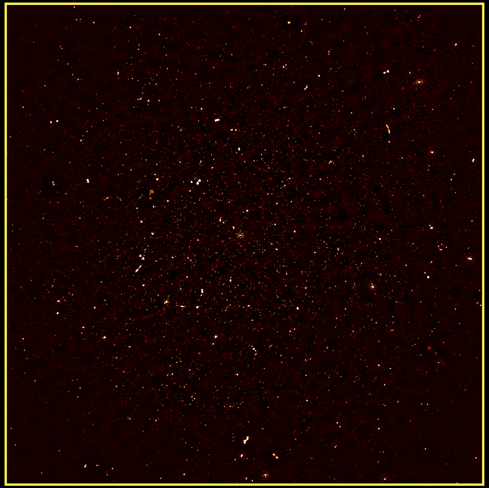
The Zooniverse - Citizen science



Thanks for all your hard work over the first few weeks of the project - we've been blown away by the response. The team will be monitoring the project less over the holiday season so be sure to tag us if you have urgent queries. Cheers - Alex

Searching for undiscovered variable radio sources in the southern sky

1 person is talking about **Bursts from Space: MeerKAT** right now.



https://www.zooniverse.org/projects/alex-andersson/bursts-from-space-meerkat

MeerKAT as a transient discovery machine

ThunderKAT is delivering impactful science

new insights in relativistic outflow, discovery of new radio transients, enabling postgraduate students to lead exciting science projects on MeerKAT

IDIA is facilitating new transient science

create solutions for SKA data flow for rapidly variable objects, create expertise in IDIA/Ilifu to deal with large complex data sets, fast imaging

MeerLICHT and MeerKAT

unique combination: real-time optical-radio observations of astrophysical transients, opening up discovery space, pathfinder for LSST + SKA transients

Patrick Woudt | Head of Department: Astronomy (University of Cape Town)

With thanks to: Rob Fender and Paul Groot

H.E.S.S. 20th anniversary conference - 17 October 2022

and the members of the ThunderKAT and MeerLICHT teams