Radio transients and variables with MeerKAT

Patrick Woudt (University of Cape Town)

Email: Patrick.Woudt@uct.ac.za

Head of Department: Astronomy
Principal investigator: ThunderKAT large survey project

With special thanks to the members of the ThunderKAT team

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

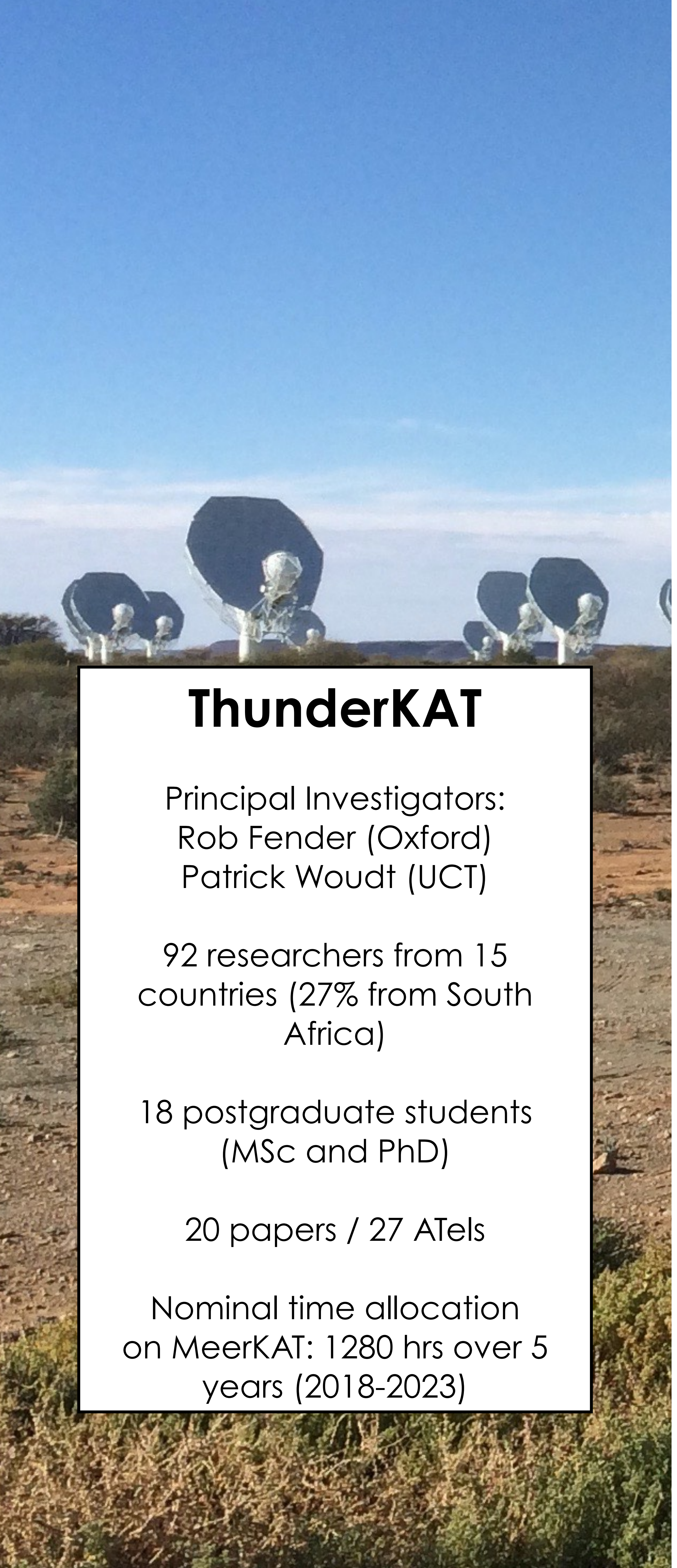
- MeerKAT was inaugurated on 13 July 2018 - **MeerKAT science ongoing**
- To be extended by 20 SKA antennas [MeerKAT extended] - baselines up to 17 km
- To be incorporated in the SKA1-MID (SKA phase 1): ~200 antennas over a 150 km baseline

Data processing infrastructure

- SARAO archive [quick look SDP image] - archive.sarao.ac.za
- Inter-University Institute for Data Intensive Astronomy (IDIA) - idia.ac.za
- Various dedicated pipelines, e.g. OxKAT (Heywood)

Data releases

- Various project-based releases



Radio Transients and Variables with MeerKAT

ThunderKAT

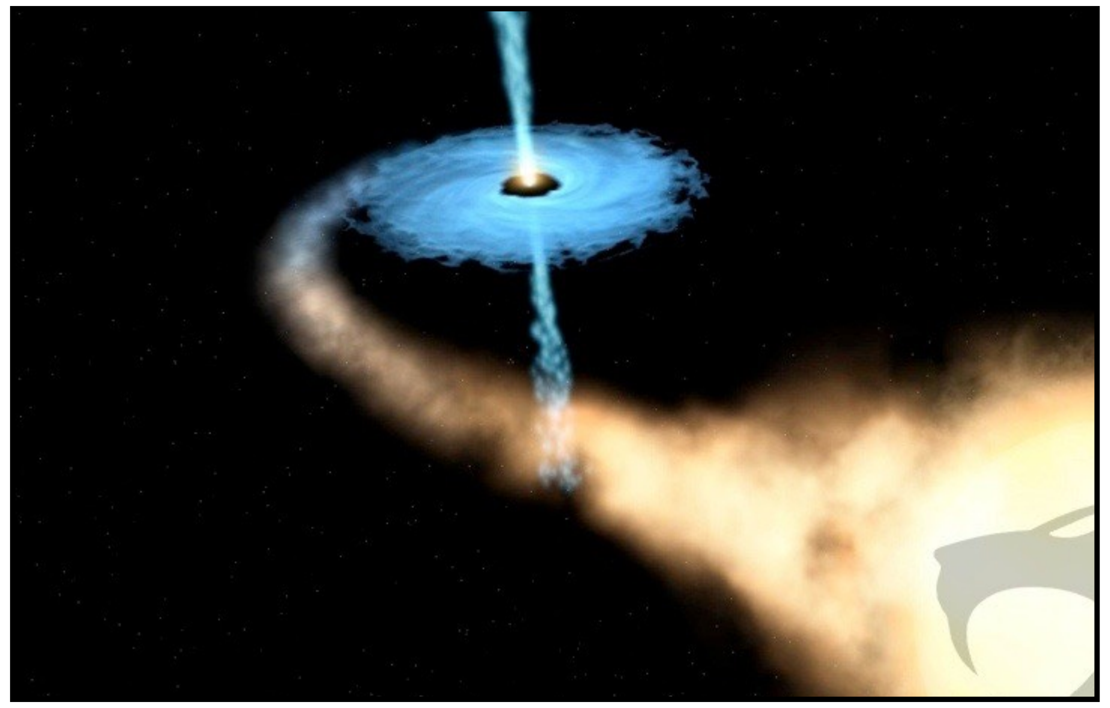
Principal Investigators:
Rob Fender (Oxford)
Patrick Woudt (UCT)

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

18 postgraduate students (MSc and PhD)

20 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
- 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:

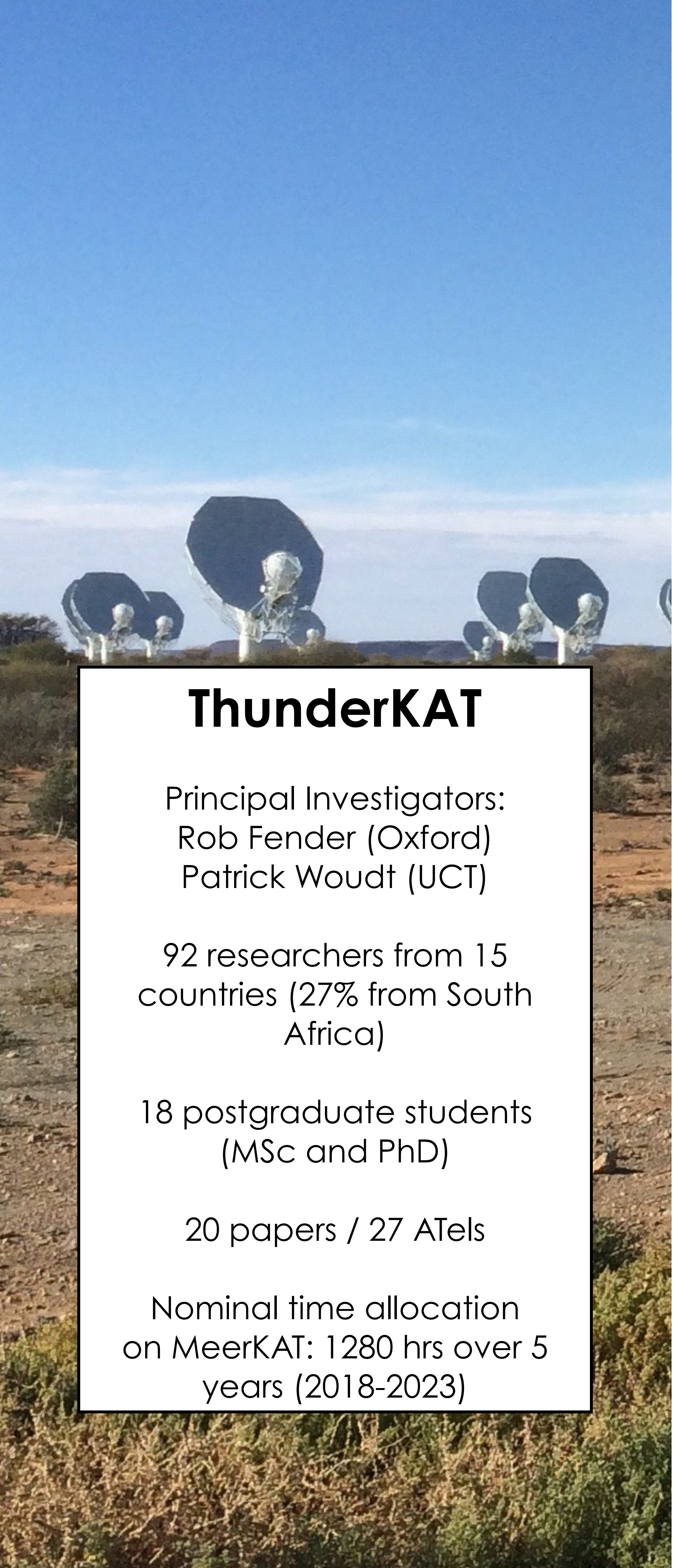
- Tidal disruption events, very high energy (VHE) gamma-ray bursts, novae, etc.

Other commensal observations with MeerKAT of transients:

- Time domain (< 2 sec): MeerTRAP

active collaboration between MeerTRAP and ThunderKAT (imaging=localisation)

Radio Transients with MeerKAT (ThunderKAT)



ThunderKAT

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

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

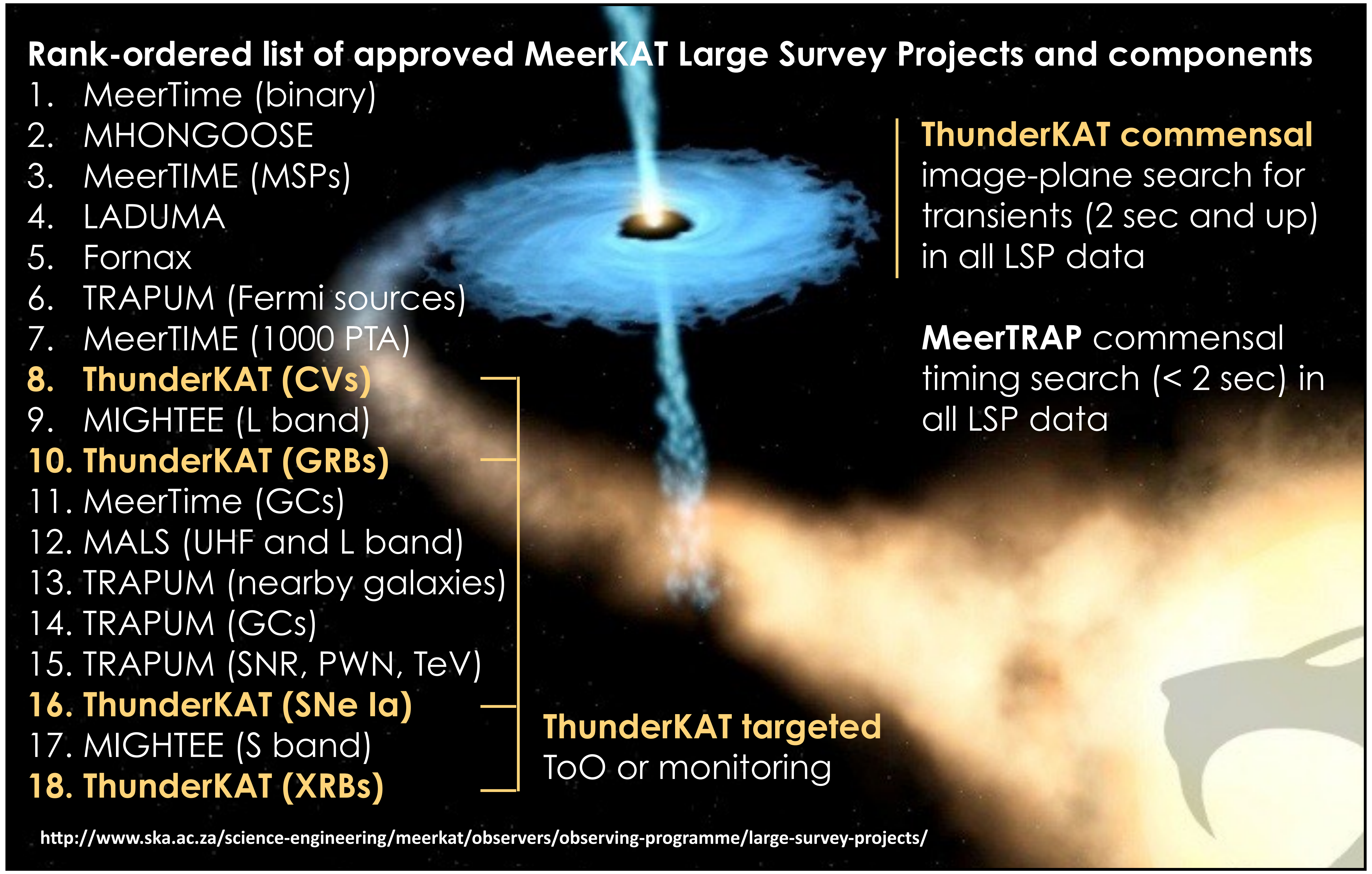
18 postgraduate students (MSc and PhD)

20 papers / 27 ATels

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

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

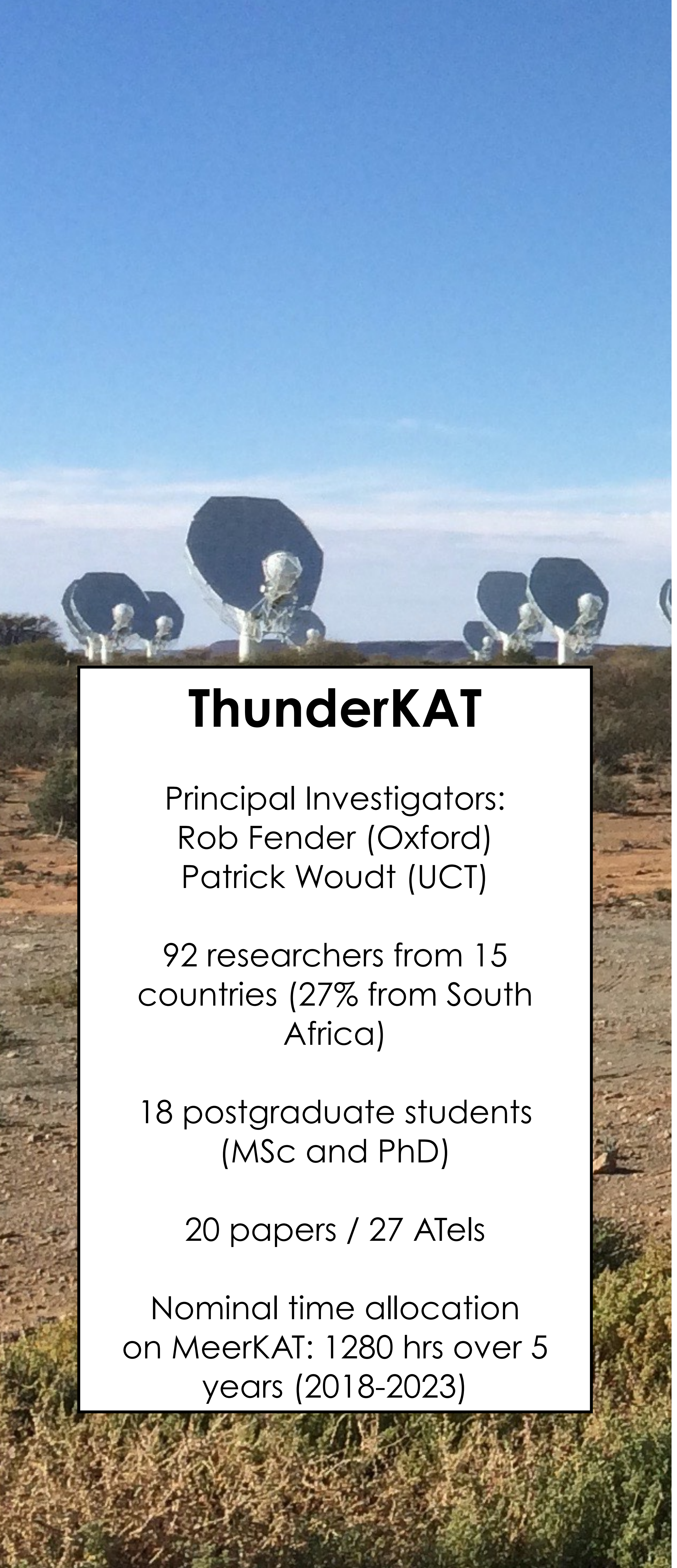
ThunderKAT targeted ToO or monitoring

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.

Radio Transients and Variables with MeerKAT



ThunderKAT

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

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

18 postgraduate students (MSc and PhD)

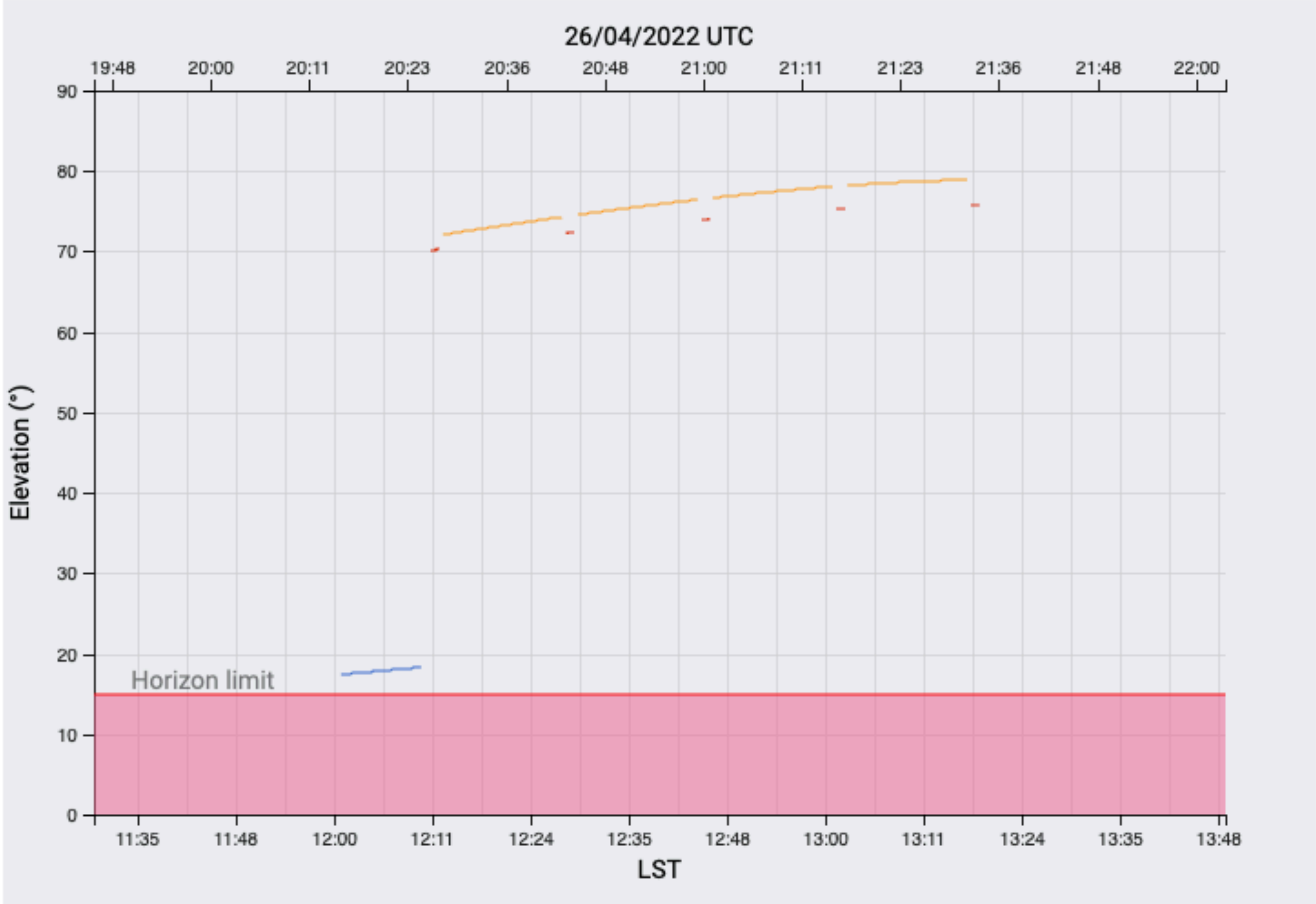
20 papers / 27 ATels

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

ThunderKAT targeted observations of transients

- Cataclysmic Variables [faint: single epoch ~2-4 hours, several epochs over ~ few days]
- Short Gamma-Ray Bursts [faint: single epoch 4-6 hours, several epochs of many weeks]
- Type Ia Supernovae [faint: single epoch 4-6 hours, several epochs of many weeks]
- X-ray Binaries [weekly monitoring when in outburst, 10-15 min per source per epoch]

GX 339-4 (XRB) observed once a week for the full duration of ThunderKAT [5 years]
planned data release of first 2.5 years of GX 339-4 observations around Q3 2022



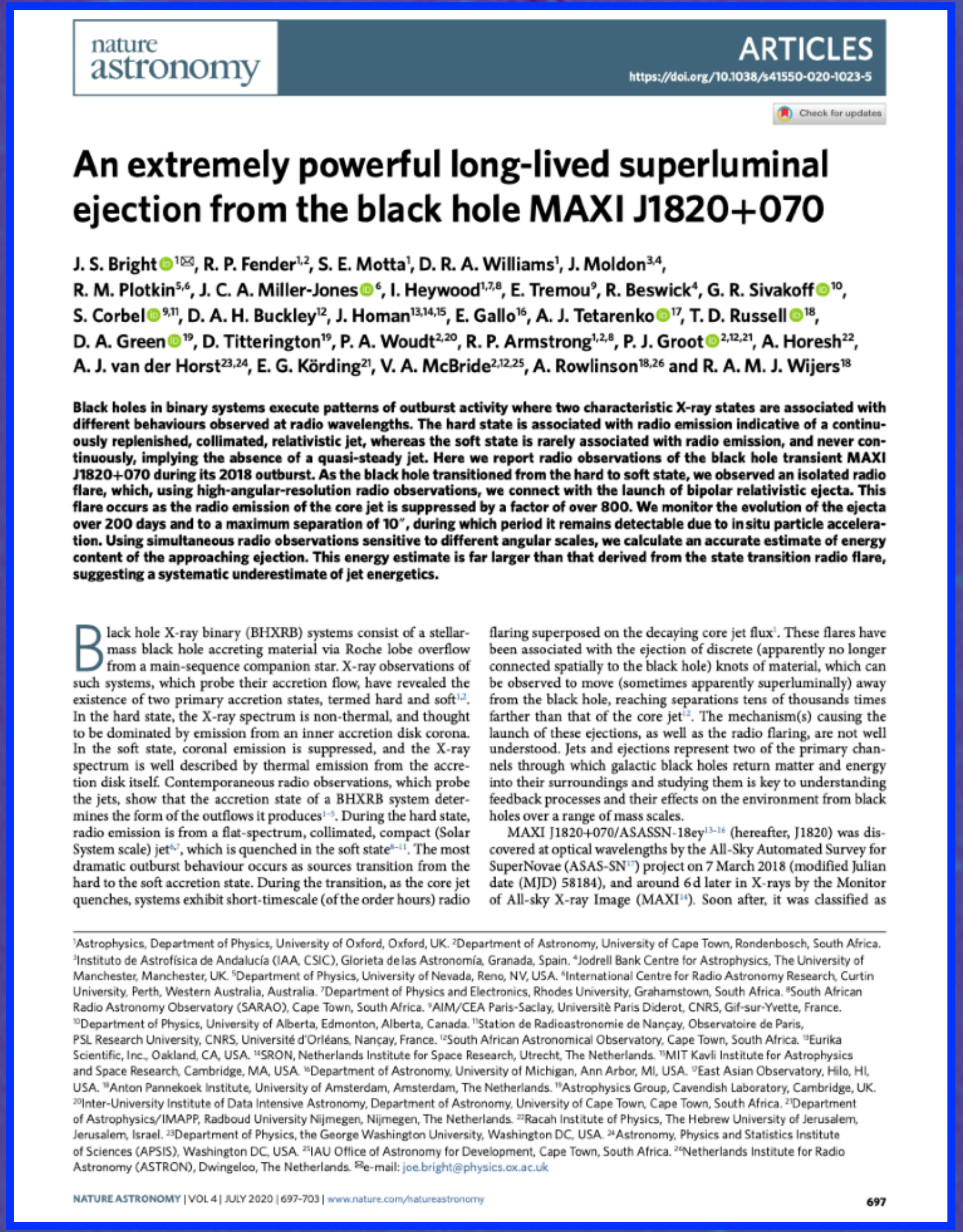
Typical observing sequence:

- start with bandpass calibrator (typically 10 min)
- gain calibrator (short, 60 sec)
- target (typically 15 min)
- repeat
- time resolution: 2 or 8 seconds
- frequency resolution: 4096 or 32768 channels

Average in time and frequency afterwards

Radio Transients and Variables with MeerKAT

Targeted observations ThunderKAT (XRBs)



nature astronomy
ARTICLES
https://doi.org/10.1038/s41550-020-1023-5
Check for updates

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.

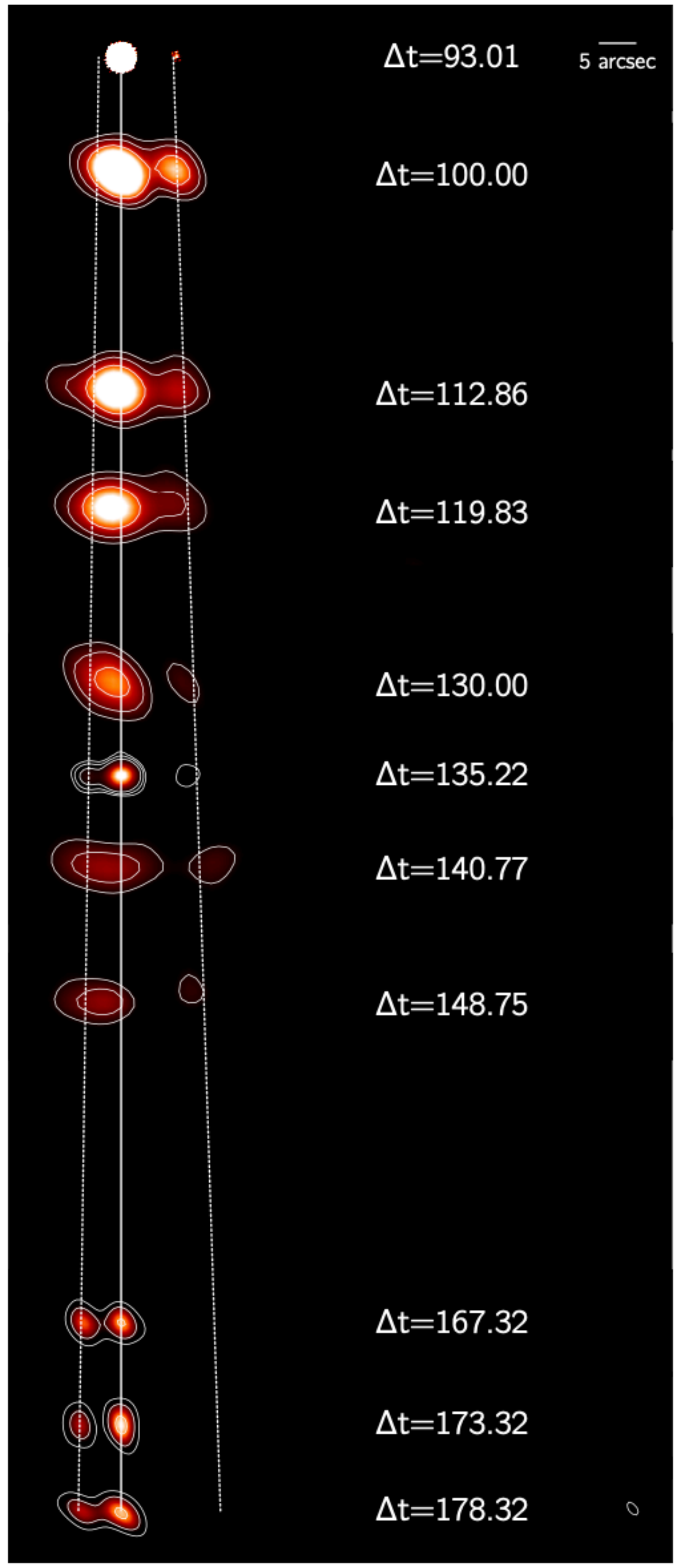
MAXI J1820+070/ASASSN-18ey[13–16] (hereafter, J1820) was discovered at optical wavelengths by the All-Sky Automated Survey for SuperNovae (ASAS-SN[17]) project on 7 March 2018 (modified Julian date (MJD) 58184), and around 6 d later in X-rays by the Monitor of All-sky X-ray Image (MAXI[14]). Soon after,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

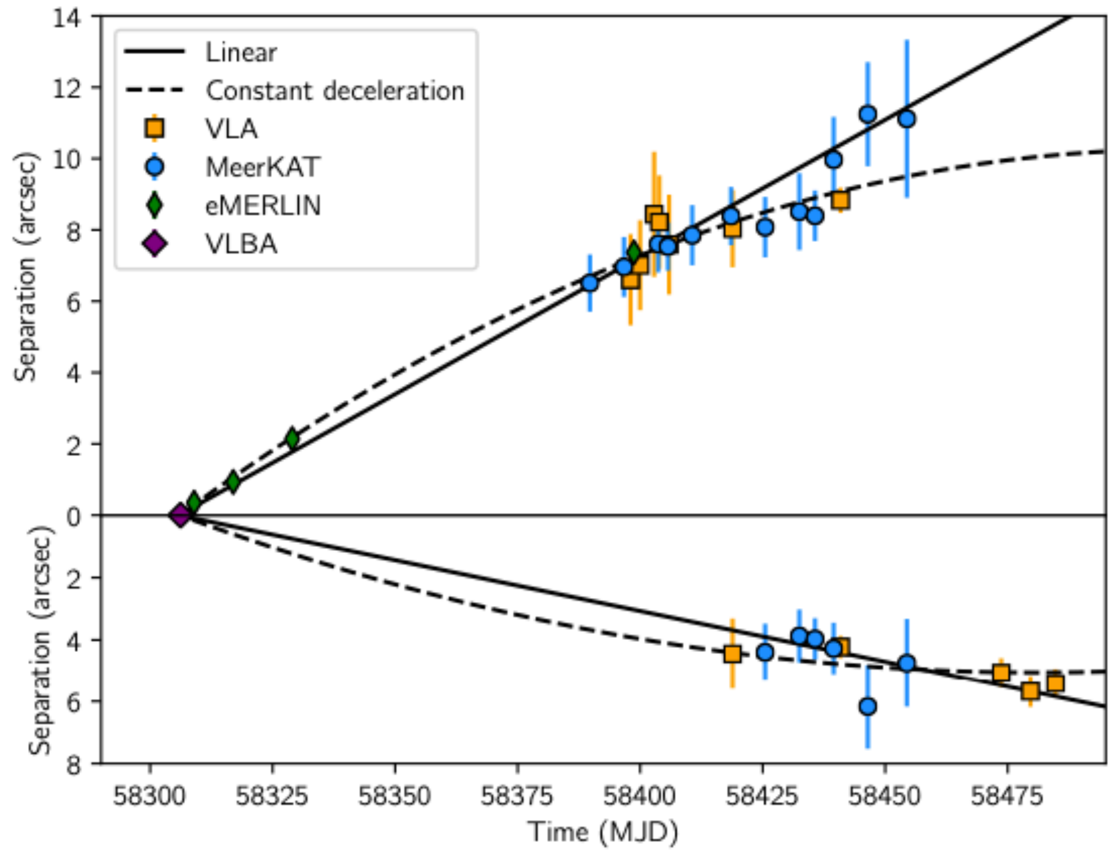
---

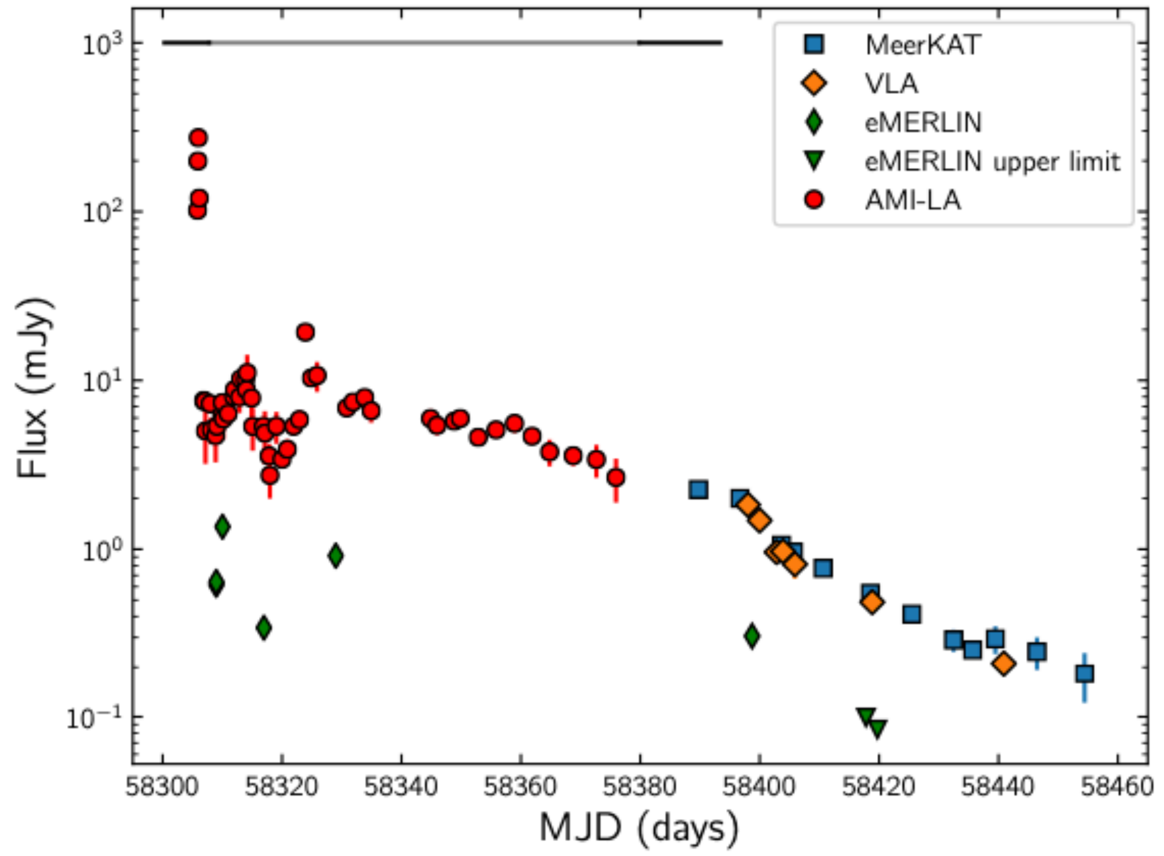
[1] Astrophysics, Department of Physics, University of Oxford, Oxford, UK. [2] Department of Astronomy, University of Cape Town, Rondenbosch, South Africa. [3] Instituto de Astrofísica de Andalucía (IAA, CSIC), Glorieta de las Astronomía, Granada, Spain. [4] Jodrell Bank Centre for Astrophysics, The University of Manchester, Manchester, UK. [5] Department of Physics, University of Nevada, Reno, NV, USA. [6] International Centre for Radio Astronomy Research, Curtin University, Perth, Western Australia, Australia. [7] Department of Physics and Electronics, Rhodes University, Grahamstown, South Africa. [8] South African Radio Astronomy Observatory (SARAO), Cape Town, South Africa. [9] AIM/CEA Paris-Saclay, Universitè Paris Diderot, CNRS, Gif-sur-Yvette, France. [10] Department of Physics, University of Alberta, Edmonton, Alberta, Canada. [11] Station de Radioastronomie de Nançay, Observatoire de Paris, PSL Research University, CNRS, Université d'Orléans, Nançay, France. [12] South African Astronomical Observatory, Cape Town, South Africa. [13] Eurika Scientific, Inc., Oakland, CA, USA. [14] SRON, Netherlands Institute for Space Research, Utrecht, The Netherlands. [15] MIT Kavli Institute for Astrophysics and Space Research, Cambridge, MA, USA. [16] Department of Astronomy, University of Michigan, Ann Arbor, MI, USA. [17] East Asian Observatory, Hilo, HI, USA. [18] Anton Pannekoek Institute, University of Amsterdam, Amsterdam, The Netherlands. [19] Astrophysics Group, Cavendish Laboratory, Cambridge, UK. [20] Inter-University Institute of Data Intensive Astronomy, Department of Astronomy, University of Cape Town, Cape Town, South Africa. [21] Department of Astrophysics/IMAPP, Radboud University Nijmegen, Nijmegen, The Netherlands. [22] Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem, Israel. [23] Department of Physics, the George Washington University, Washington DC, USA. [24] Astronomy, Physics and Statistics Institute of Sciences (APSIS), Washington DC, USA. [25] IAU Office of Astronomy for Development, Cape Town, South Africa. [26] Netherlands Institute for Radio Astronomy (ASTRON), Dwingeloo, The Netherlands. ✉e-mail: joe.bright@physics.ox.ac.uk

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

Radio Transients and Variables with MeerKAT

Targeted observations ThunderKAT (XRBs)

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

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

E. Tremou,[1★] S. Corbel,[1,2★] R. P. Fender,[3,4] P. A. Woudt,[4] J. C. A. Miller-Jones ,[5] S. E. Motta ,[3] I. Heywood,[3,6] R. P. Armstrong,[3,4,7] P. Groot,[4,8,9] A. Horesh,[10] A. J. van der Horst,[11,12] E. Koerding,[9] K. P. Mooley ,[13,14,15] A. Rowlinson [16,17] and R. A. M. J. Wijers[16]

[1] *AIM/CEA Paris-Saclay, Université Paris Diderot, CNRS, F-91191 Gif-sur-Yvette, France*
[2] *Station de Radioastronomie de Nançay, Observatoire de Paris, PSL Research University, CNRS, Univ. Orléans, F-18330 Nançay, France*
[3] *Astrophysics, Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK*
[4] *Inter-University Institute for Data-Intensive Astronomy, Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa*
[5] *International Centre for Radio Astronomy Research, Curtin University, GPO Box U1987, Perth, WA 6845, Australia*
[6] *Department of Physics and Electronics, Rhodes University, PO Box 94, Grahamstown 6140, South Africa*
[7] *South African Radio Astronomy Observatory, 2 Fir Street, Black River Park, Observatory, Cape Town 7925, South Africa*
[8] *South African Astronomical Observatory, PO Box 9, Observatory, Cape Town 7935, South Africa*
[9] *Department of Astrophysics/IMAPP, Radboud University Nijmegen, PO Box 9010, NL-6500 GL Nijmegen, the Netherlands*
[10] *Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel*
[11] *Department of Physics, The George Washington University, 725 21st Street NW, Washington, DC 20052, USA*
[12] *Astronomy, Physics and Statistics Institute of Sciences (APSIS), 725 21st Street NW, Washington, DC 20052, USA*
[13] *Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK*
[14] *National Radio Astronomy Observatory, Socorro, NM 87801, USA*
[15] *Caltech, 1200 E. California Blvd. MC 249-17, Pasadena, CA 91125, USA*
[16] *Anton Pannekoek Institute, University of Amsterdam, Postbus 94249, NL-1090 GE Amsterdam, the Netherlands*
[17] *Netherlands Institute for Radio Astronomy (ASTRON), Oude Hoogeveensedijk 4, NL-7991 PD Dwingeloo, the Netherlands*

Accepted 2020 February 3. Received 2020 January 17; in original form 2019 December 5

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.

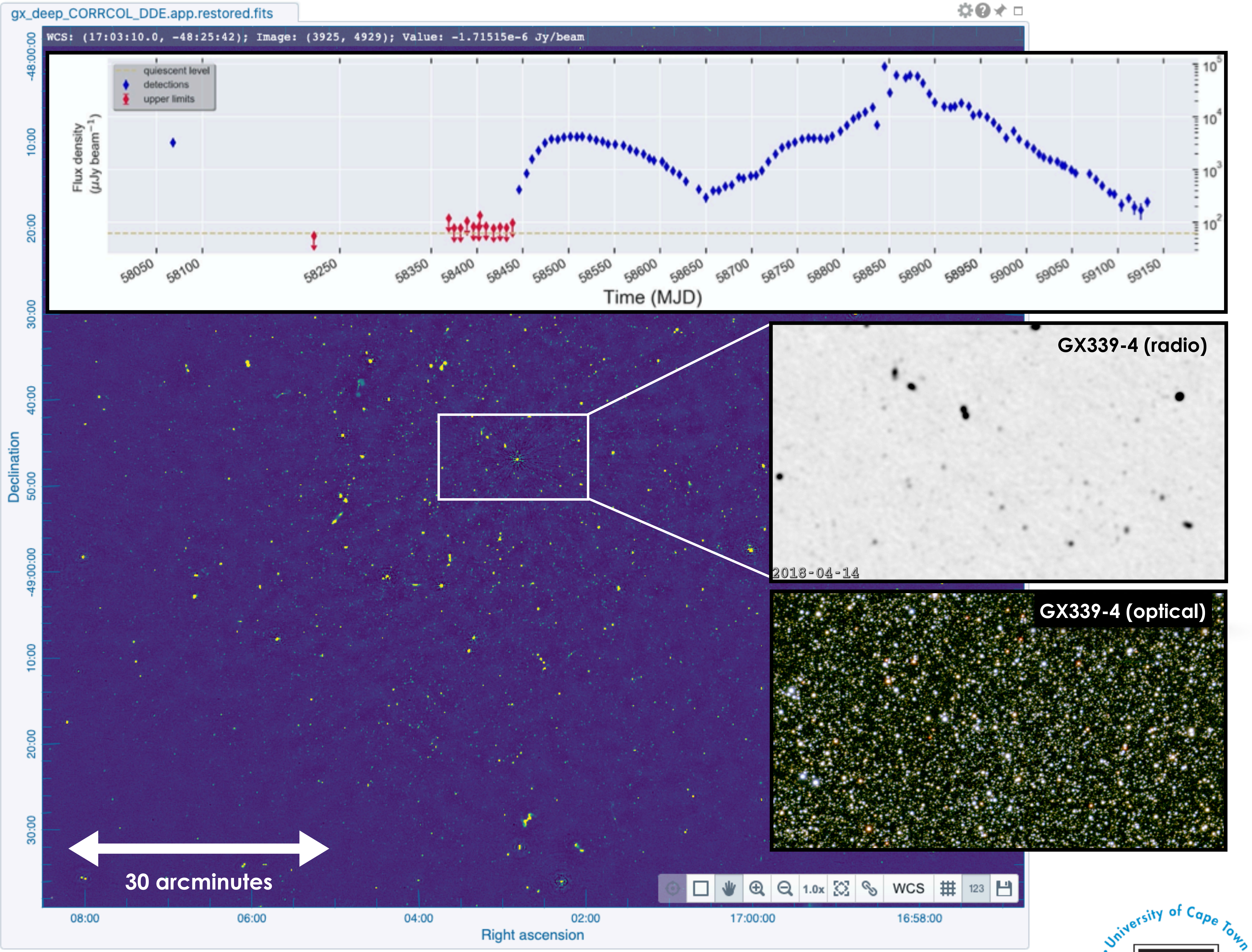
[★] E-mail: evangelia.tremou@cea.fr (ET), stephane.corbel@cea.fr (SC)

Published by Oxford University Press on behalf of the Royal Astronomical Society

The black hole X-ray binary GX 339-4

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

Tremou, E., et *al.* MNRAS Letters 493 (2020) L132



```
WCS: (17:03:10.0, -48:25:42); Image: (3925, 4929); Value: -1.71515e-6 Jy/beam
```

Radio Transients and Variables with MeerKAT

Commensal observations ThunderKAT

Monthly Notices of the Royal Astronomical Society
MNRAS **491,** 560–575 (2020) doi:10.1093/mnras/stz3027
Advance Access publication 2019 October 30

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

L. N. Driessen,[1★] I. McDonald,[1] D. A. H. Buckley,[2] M. Caleb,[1] E. J. Kotze,[2,3] S. B. Potter,[2] K. M. Rajwade,[1] A. Rowlinson,[4,5] B. W. Stappers,[1] E. Tremou,[6] P. A. Woudt,[7] R. P. Fender,[7,8] R. Armstrong,[7,9] P. Groot,[2,7,10] I. Heywood,[8,11] A. Horesh,[12] A. J. van der Horst,[13,14] E. Koerding,[10] V. A. McBride,[2,15,16] J. C. A. Miller-Jones,[17] K. P. Mooley[18,19,20] and R. A. M. J. Wijers[4]

Affiliations are listed at the end of the paper

Accepted 2019 October 18. Received 2019 October 18; in original form 2019 August 14

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

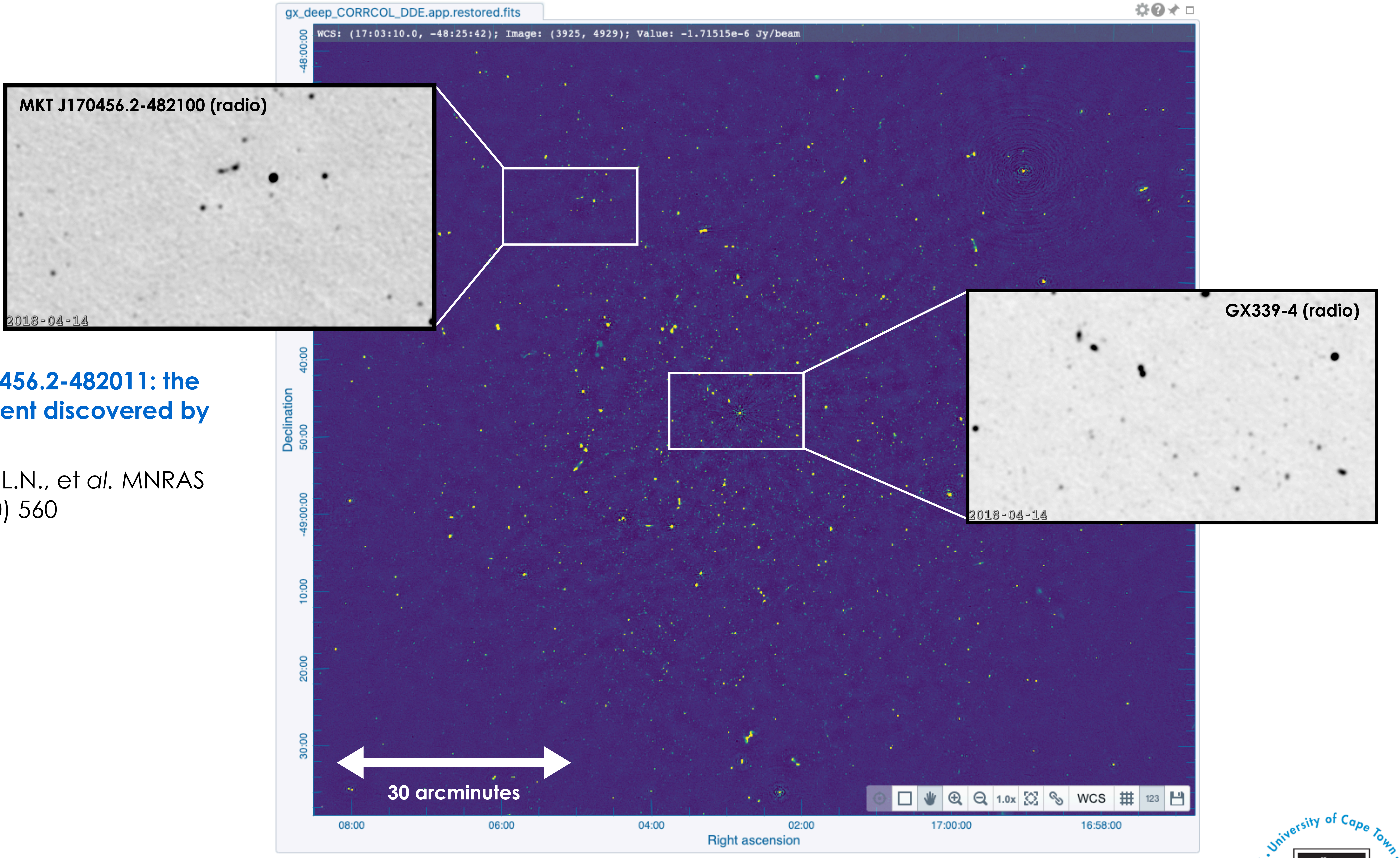
The radio sky contains many variable and transient sources, often found in follow-up observations of transients detected at other wavelengths such as optical, gamma-ray, and X-ray (e.g. Sood & Campbell-Wilson 1994; Zauderer et al. 2011; Chandra & Frail 2012; Horesh et al. 2013; Fong et al. 2015; Marsh 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;

---

* E-mail: laura@driessen.net.au

The first radio transient discovered by MeerKAT



gx_deep_CORRCOL_DDE.app.restored.fits

WCS: (17:03:10.0, -48:25:42); Image: (3925, 4929); Value: -1.71515e-6 Jy/beam

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

Driessen, L.N., et *al.* MNRAS 491 (2020) 560

Radio Transients and Variables with MeerKAT

Commensal observations ThunderKAT

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **512,** 5037–5066 (2022)
Advance Access publication 2022 March 21

https://doi.org/10.1093/mnras/stac756

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

L. N. Driessen,[1★] B. W. Stappers,[1] E. Tremou,[2] R. P. Fender,[3,4] P. A. Woudt,[3] R. Armstrong,[3,5] S. oemen,[6] P. Groot,[3,6,7] I. Heywood,[4,8] A. Horesh,[9] A. J. van der Horst,[10,11] E. Koerding,[6] V. A. McBride,[7,12,13] J. C. A. Miller-Jones,[14] K. P. Mooley,[15,16] A. Rowlinson[17,18] and R. A. M. J. Wijers[17]

[1] *Jodrell Bank Centre for Astrophysics, Department of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, UK*
[2] *LESIA, Observatoire de Paris, CNRS, PSL Research University, Sarbonne Universite, Universite de Paris, Meudon, F-92190, France*
[3] *Inter-University Institute for Data Intensive Astronomy, Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa*
[4] *Department of Physics, Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK*
[5] *South African Radio Astronomy Observatory, 2 Fir Street, Black River Park, Observatory, Cape Town 7925, South Africa*
[6] *Department of Astrophysics/IMAPP, Radboud University, PO Box 9010, NL-6500 GL Nijmegen, the Netherlands*
[7] *South African Astronomical Observatory, PO Box 9, Observatory 7935, South Africa*
[8] *Department of Physics and Electronics, Rhodes University, PO Box 94, Makhanda 6140, South Africa*
[9] *Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel*
[10] *Department of Physics, The George Washington University, 725 21st Street NW, Washington, DC 20052, USA*
[11] *Astronomy, Physics, and Statistics Institute of Sciences (APSIS), 725 21st Street NW, Washington, DC 20052, USA*
[12] *Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa*
[13] *IAU Office of Astronomy for Development, Cape Town 7935, South Africa*
[14] *International Centre for Radio Astronomy Research – Curtin University, GPO Box U1987, Perth, WA 6845, Australia*
[15] *National Radio Astronomy Observatory, Socorro, NM 87801, USA*
[16] *Caltech, 1200 E. California Blvd. MC 249-17, Pasadena, CA 91125, USA*
[17] *Anton Pannekoek Institute, University of Amsterdam, Postbus 94249, NL-1090 GE Amsterdam, the Netherlands*
[18] *Netherlands Institute for Radio Astronomy (ASTRON), Oude Hoogeveensedijk 4, NL-7991 PD Dwingeloo, the Netherlands*

Accepted 2022 March 14. Received 2022 February 17; in original form 2021 July 11

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

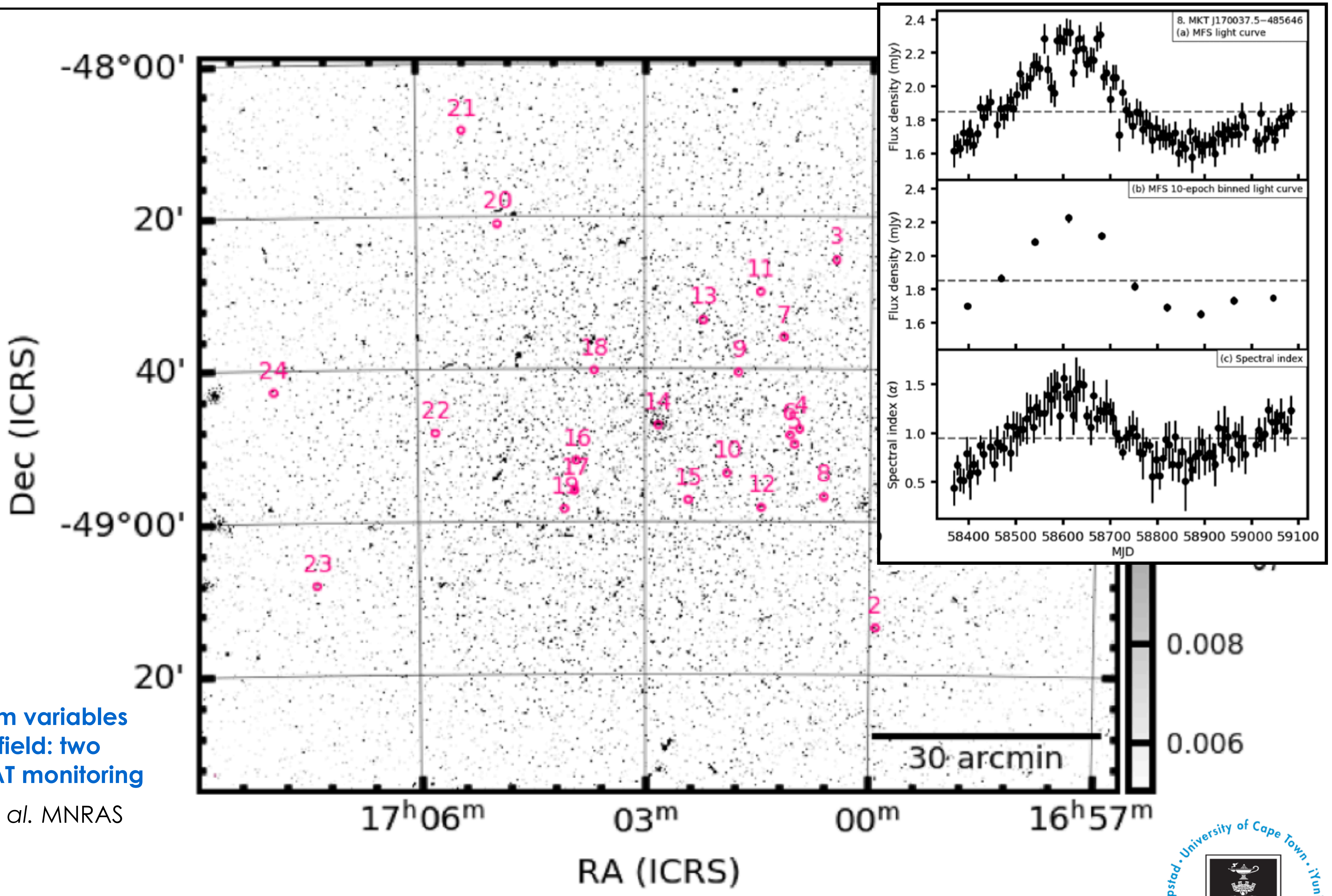
We are entering a new era of radio astronomy where we can execute untargeted, image-plane searches for variable and transient sources using sensitive instruments with wide field capabilities. Instruments such as the Australian Square Kilometre Array Pathfinder (ASKAP;[1] Hotan et al. 2021), the Karl 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

---

* E-mail: laura@driessen.net.au
[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.

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

Radio Transients and Variables with MeerKAT

Commensal observations ThunderKAT

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

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

A. Rowlinson,[1,2]★ J. Meijn,[1] J. Bright,[3] A.J. van der Horst,[4] S. Chastain,[4] S. Fijma,[1] R. Fender,[5] I. Heywood,[5,6,7] R.A.M.J. Wijers,[1] P.A. Woudt,[8] A. Andersson,[5] G.R. Sivakoff,[9] E. Tremou,[10] L.N. Driessen,[11]

[1] *Anton Pannekoek Institute, University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands*
[2] *ASTRON, the Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4, 7991 PD, Dwingeloo, The Netherlands*
[3] *Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA*
[4] *Department of Physics, The George Washington University, 725 21st Street NW, Washington, DC 20052, USA*
[5] *Astrophysics, Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK*
[6] *Department of Physics and Electronics, Rhodes University, PO Box 94, Makhanda 6140, South Africa*
[7] *South African Radio Astronomy Observatory, 2 Fir Street, Observatory 7925, South Africa*
[8] *Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa*
[9] *Department of Physics, University of Alberta, CCIS 4-181, Edmonton, AB T6G 2E1, Canada*
[10] *National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801, USA*
[11] *CSIRO, Space and Astronomy, PO Box 1130, Bentley, WA 6102, Australia*

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

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

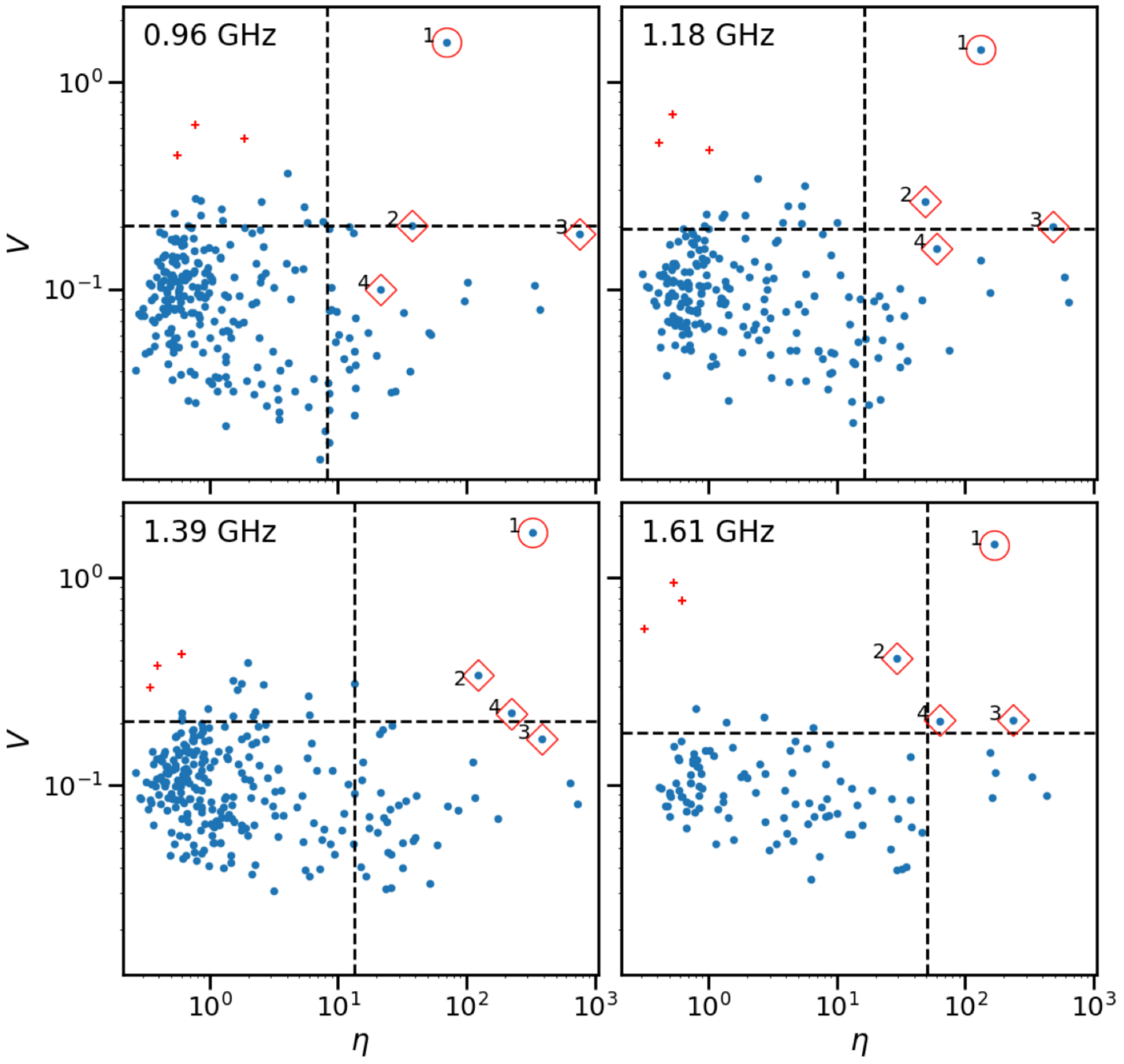
The past decade has been the renaissance of the radio transient sky. While a number of transient and variable radio sources were known for many years from targeted searches of sources discovered at other observing frequencies, for example X-ray binaries (XRBs), active galactic nuclei (AGNs) and gamma-ray 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

★ E-mail: b.a.rowlinson@uva.nl

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.

Radio Transients and Variables with MeerKAT

Commensal observations ThunderKAT

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

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

A. Rowlinson,[1,2]★ J. Meijn,[1] J. Bright,[3] A.J. van der Horst,[4] S. Chastain,[4] S. Fijma,[1] R. Fender,[5] I. Heywood,[5,6,7] R.A.M.J. Wijers,[1] P.A. Woudt,[8] A. Andersson,[5] G.R. Sivakoff,[9] E. Tremou,[10] L.N. Driessen,[11]

[1] *Anton Pannekoek Institute, University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands*
[2] *ASTRON, the Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4, 7991 PD, Dwingeloo, The Netherlands*
[3] *Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA*
[4] *Department of Physics, The George Washington University, 725 21st Street NW, Washington, DC 20052, USA*
[5] *Astrophysics, Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK*
[6] *Department of Physics and Electronics, Rhodes University, PO Box 94, Makhanda 6140, South Africa*
[7] *South African Radio Astronomy Observatory, 2 Fir Street, Observatory 7925, South Africa*
[8] *Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa*
[9] *Department of Physics, University of Alberta, CCIS 4-181, Edmonton, AB T6G 2E1, Canada*
[10] *National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801, USA*
[11] *CSIRO, Space and Astronomy, PO Box 1130, Bentley, WA 6102, Australia*

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

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

---

★ E-mail: b.a.rowlinson@uva.nl

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

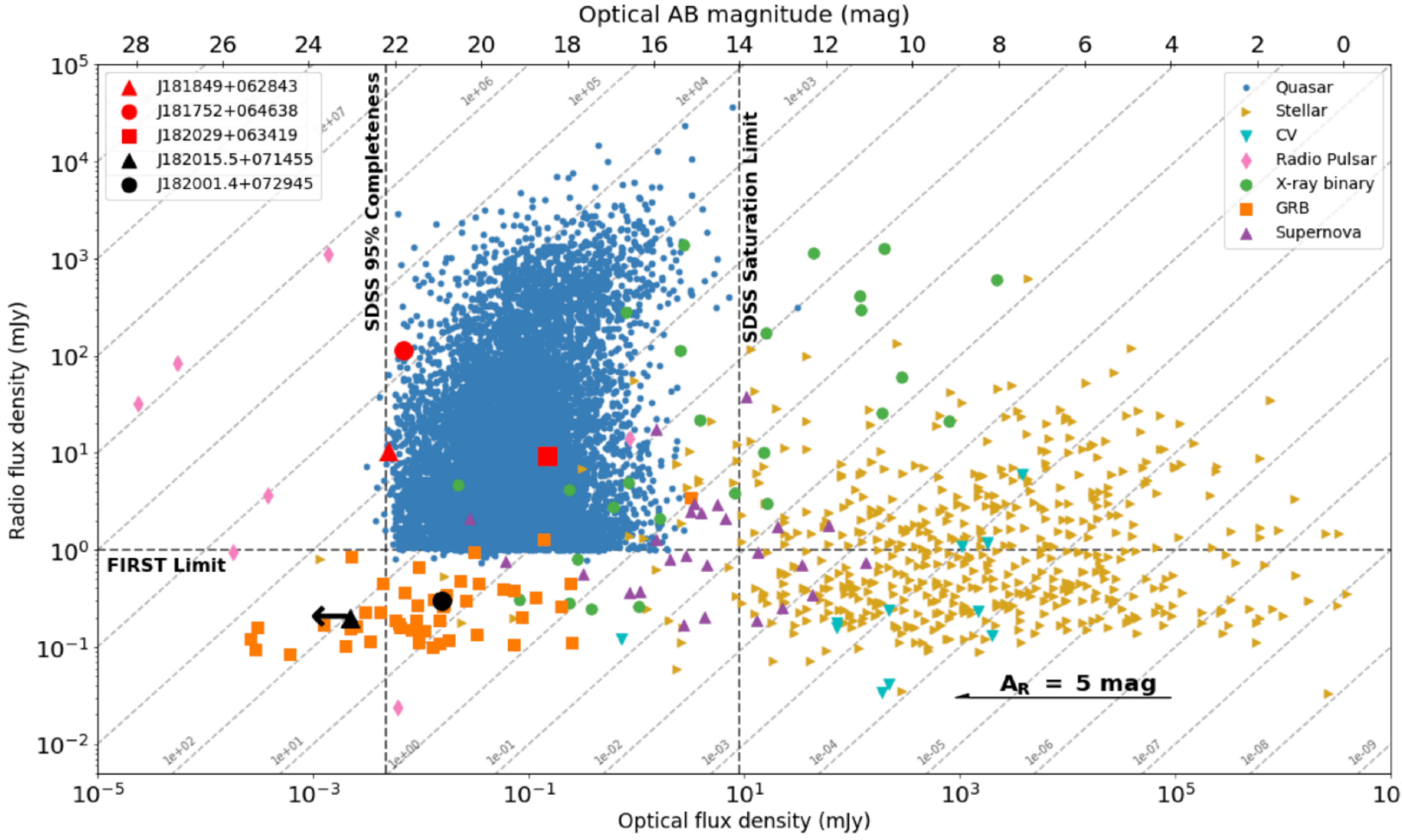
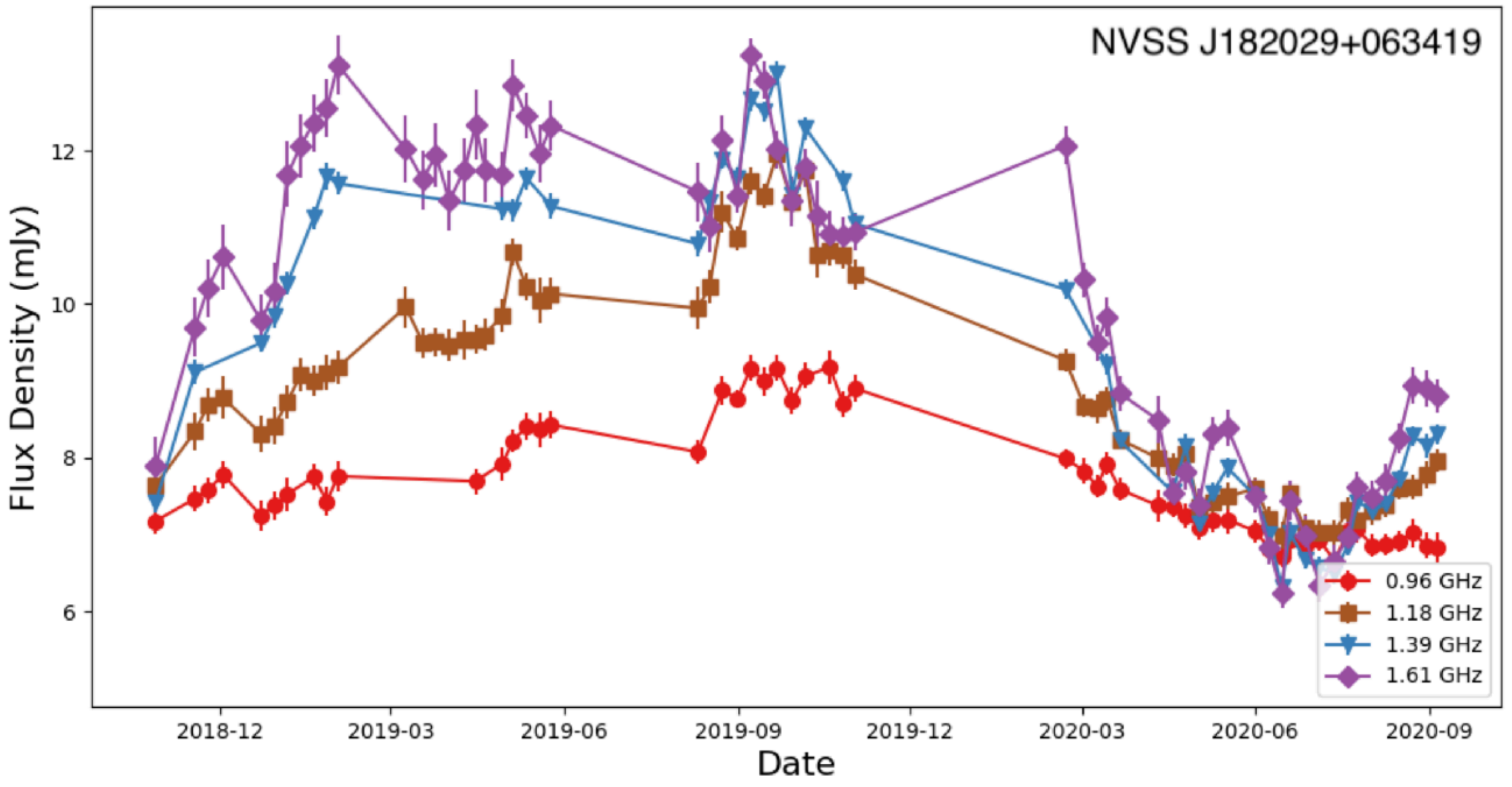


Figure 7. Radio flux density versus optical flux density for different populations of transient and variable sources, adapted from Figure 1 in Stewart et al. (2018). The two unidentified variable sources identified in Section 3.1 are shown with black symbols. The three variable sources identified in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



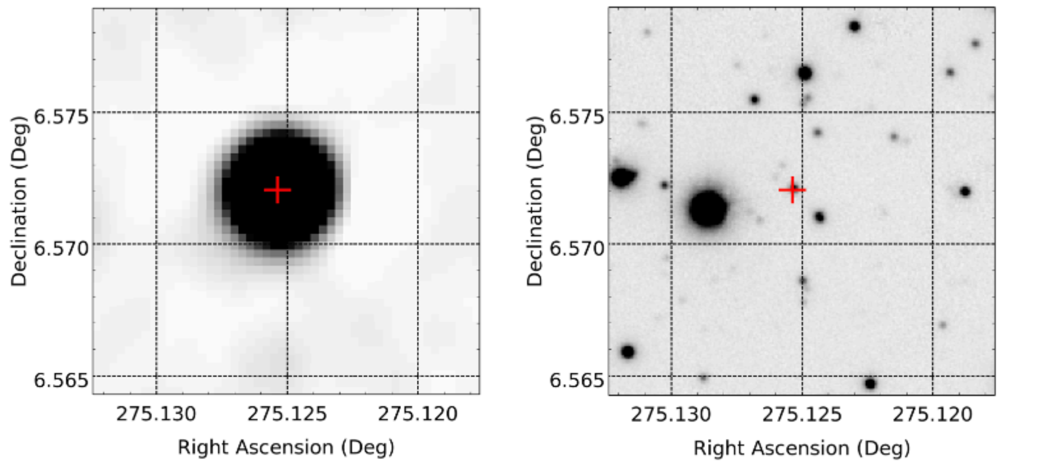


Figure C5. NVSS J182029+063419. Left: deep MeerKAT image. Right: PanSTARRS z band image. The red plus symbol shows the location of the source.

- 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)

Radio Transients and Variables with MeerKAT

Key parameters from the observations:

- Frequency range: UHF, L or S-band
- Frequency resolution: 4096 or 32768 channels [typically binned to 107 or 215 MHz]
- Time information: UTC start, end, etc.
- Time resolution: 2 or 8 seconds [typically binned to one block length: 10-15 min]

Key parameters from the analysis (with uncertainties, respectively):

- Position
- Proper motion of (relativistic) ejecta (in some cases)
- Flux (Stokes I) for each frequency bin
- Polarisation measurement (e.g. Stokes V) for each frequency bin
- Spectral index [across 4 or 8 frequency bands with MeerKAT L-band]

Key parameters for the light curve:

- Sampling time (cadence) - can be averaged to different time scales to explore variability on different time scales
- Note: for commensal transient searches, cadence is determined by others
- TraP variability indices: V and η