National Research Foundation

SCiENCE MaTTERS

Vol: 3 | ISSUE:3 | SAAO SPECIAL EDITION

COSMOLOGY WITH THE HIRAX EXPERIMENT

From Big Data TO BIG IDEA

SAAO in the 21st CENTURY

DANCING with the STARS

Astronomy in South Africa Before 1972

THE INTELLIGENT OBSERVATORY and Things That Go Bump In the Night

SA's MeerKAT Telescope - NEW WINDOW INTO GALAXY EVOLUTION

CONTENT PAGE

SCiENCE MaTTERS

As we reach the milestone of 200 hundred years of astronomy research in South Africa, it's worth reflecting on our past and what the future holds. This special edition of Science Matters focuses on the facilities, infrastructure and research themes through which South Africa punches well above its weight in the global astronomy endeavour.

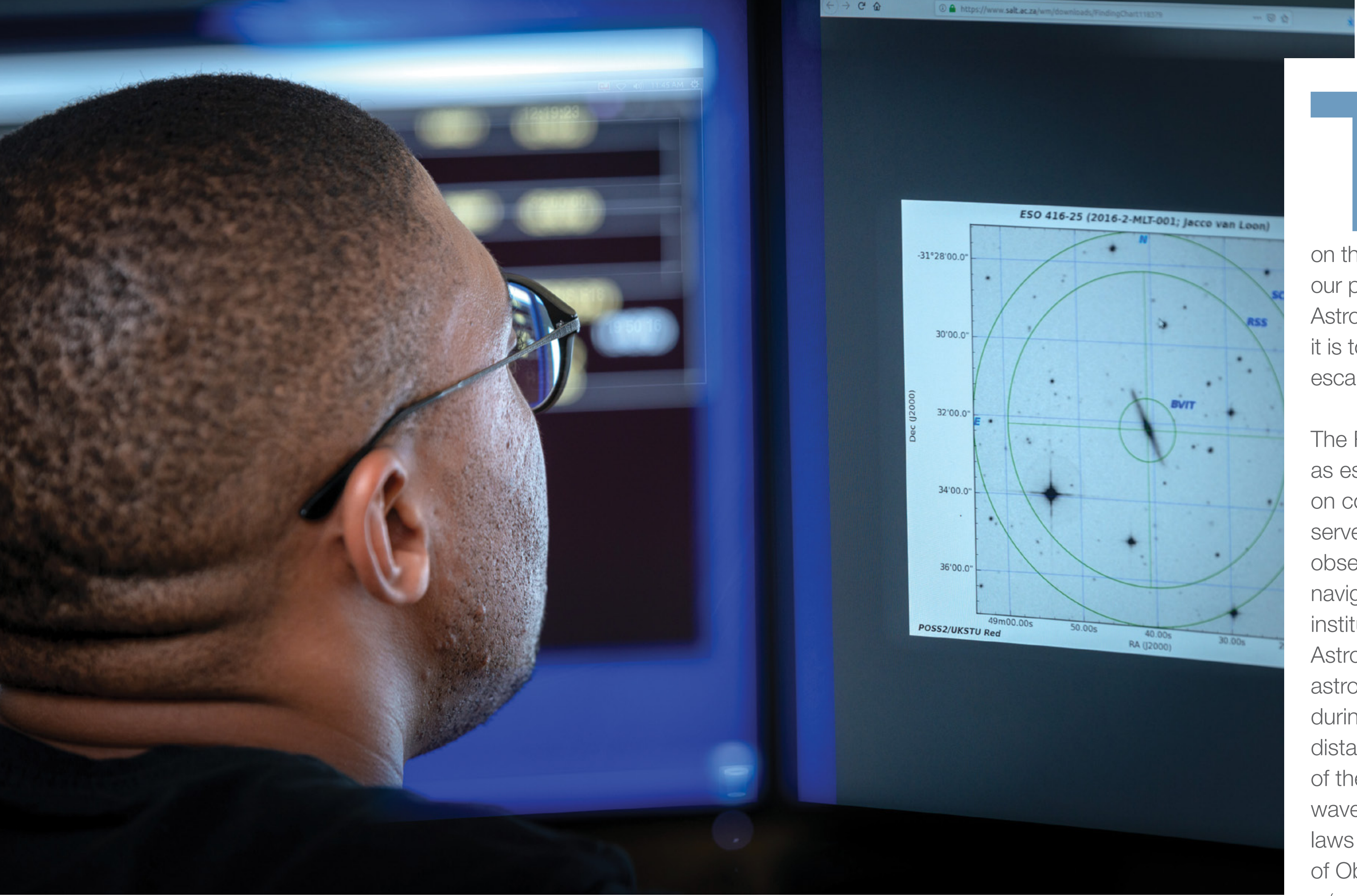
We host a variety of world-leading telescopes such as the Southern African Large Telescope (SALT) and *MeerKAT* which are facilitating new discoveries in stellar and galaxy evolution. Telescope facilities are being built, adapted or mobilised to spot 'transients' and 'fast radio bursts'. Big data processing facilities have also been established, preparing us for the Square Kilometre Array and South Africa's role in the fourth industrial revolution.

Thanks to all the researches who have contributed articles to this issue.

This issue of Science Matters is edited by Dr Daniel Cunnama and Dr Jacinta Delhaize.

SCiENCE MaTTERS is produced by:
NRF Corporate Communications Office
Meiring Naudé Rd, Brummeria, Pretoria
Email: sciencematters@nrf.ac.za
Web: www.nrf.ac.za/science-matters

NRF National Research Foundation



The South African Astronomical Observatory IN THE 21ST CENTURY

by Vanessa McBride & Petri Vaisanen

Looking to the future of the South African Astronomical Observatory

SAAO

The commemoration of the bicentenary of astronomy in South Africa offers us an opportunity to look to the future and the exciting scientific and technical developments on the way. But it's alsoa moment to consider our past: how it has shaped the South African Astronomical Observatory (SAAO) into the institution it is today, and how we can both build on it and escape it to realise the future of the SAAO.

The Royal Observatory at the Cape of Good Hope, as established in 1820 by the British, was founded on colonial and imperialist ambitions. Before it served the scientific community, it was a naval observatory, with the focus on timekeeping and navigation. Out of these roots grew a scientific institution that would become the South African Astronomical Observatory (SAAO) in 1972. New astronomical discoveries have been ubiquitous during this time, ranging from a measurement of the distance to Alpha Centauri in 1842 to observations of the first optical counterpart to a gravitational wave event in 2017. While bound by apartheid laws of the time, the SAAO, situated in the suburb of Observatory, Cape Town, was also embedded in a 'grey' suburb - one of the few areas where South Africans of all races lived together.

Today, just like its home suburb, the SAAO is an eclectic juxtaposition of the old and the new. A beautiful, wood-panelled library houses the first volume of the *Monthly Notices of the Royal Astronomical Society*. Behind it, a state-of-the-art workshop manufactures, to micrometre precision, bespoke components for cameras and spectrographs. The observing station is located 360km away, just outside the Northern Cape town of Sutherland. The Southern African Large Telescope (SALT) stands as a sentinel on the observing plateau, a working monument to the audacious vision of the South African government and science community. While the town of Sutherland has been reshaped by astro-tourism, its ongoing development challenges are also a stark reminder of the realities of poverty, unemployment and inequality that face South African society.

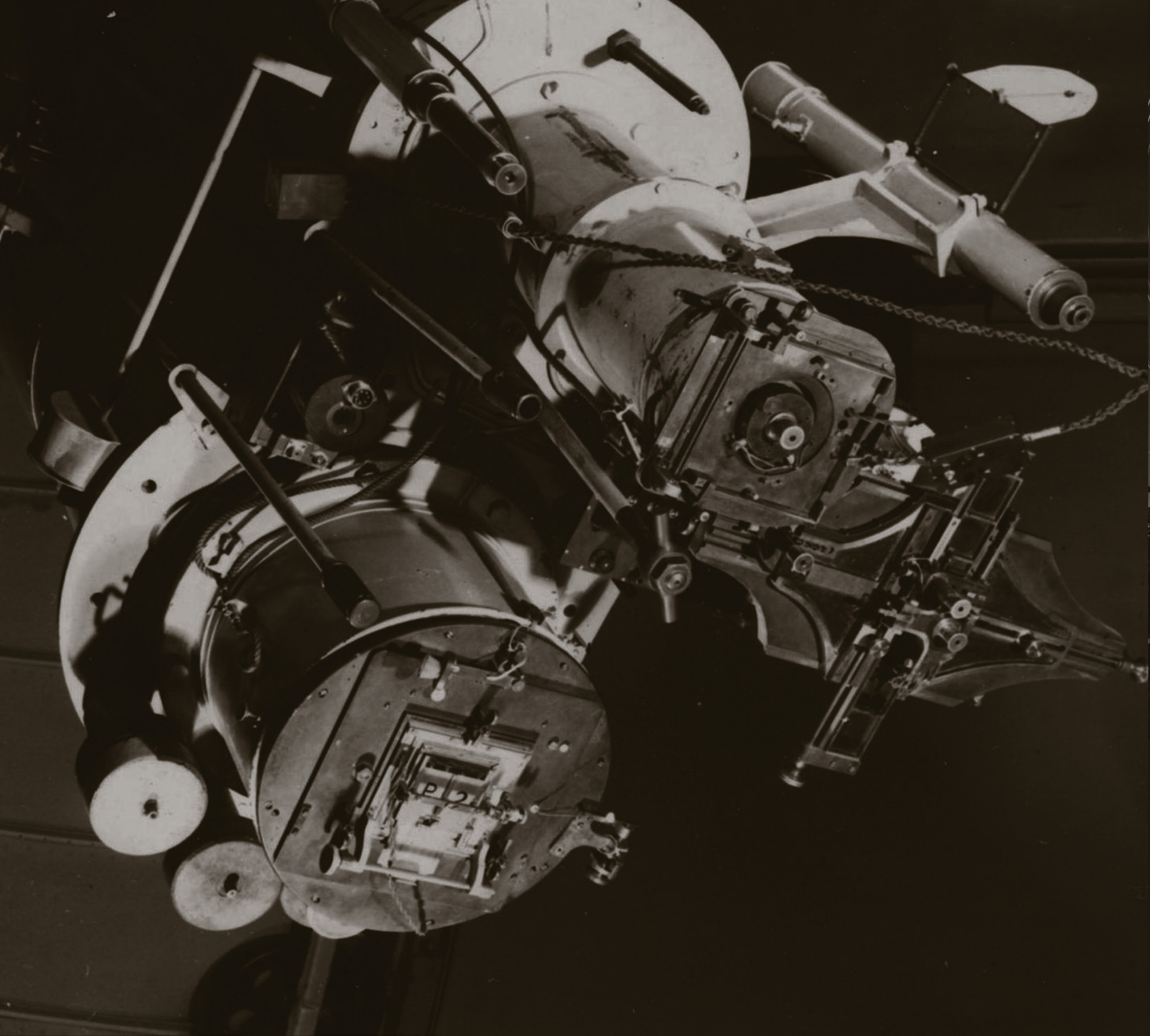
Science and the society in which it is embedded are inextricably intertwined. History has left us with a legacy that pervades the very fabric of our society: we must unlearn decades of discrimination. As we take stock of the immense leaps forward in our astronomical knowledge over the last two hundred years, we see also how science in South Africa must diversify its workforce. Over the last decade, the SAAO, while delivering world-class scientific research, has been at the heart of initiatives designed to address the inequalities faced by women and black scientists.

This work is far from done. South Africa's historically disadvantaged institutions are stepping forward to claim their places on the stage of blue-sky science, and a network of astronomers is burgeoning across the African continent, consolidating in the newly revitalised African Astronomical Society. On the horizon is the biggest meeting on the astronomy calendar, the General Assembly of the International Astronomical Union. The meeting in 2024 will be the first General Assembly held on the African continent since the establishment of the Union over 100 years ago - securing the recognition of Africa's contribution to global science. This is a pivot point for the South African Astronomical Observatory. It's an opportunity for both science and society. Bring on the next 200 years!

About the Authors:

Prof Petri Vaisanen obtained his PhD from the University of Helsinki, and after spells in USA and Chile, he joined SALT and SAAO in 2004. He currently serves as the Director of the SAAO, while his own research is on colliding and interacting galaxies and violent star formation.

Assoc. Prof Vanessa McBride is an astronomer at the IAU's Office of Astronomy for Development and Head of Research at the South African Astronomical Observatory. She is also an adjunct associate professor in the Department of Astronomy at the University of Cape Town.



Highlights of Astronomy
IN SOUTH AFRICA BEFORE 1972

By Ian Glass

Some of the most exciting scientific achievements in South Africa's Astronomical research

SAAO

Astronomical research in South Africa began in the mid-18th century with the visit of the French Academician Nicolas-Louis de La Caille in 1751-1753. La Caille undertook a careful examination of every square degree of the Southern Sky, resulting in the first truly comprehensive sky survey ever made (in either hemisphere!)

His pioneering work was followed by the establishment of the Royal Observatory, Cape of Good Hope, in 1820. For much of its history this, the first permanent observatory in South Africa, was the major contributor to positional astronomy in the Southern Hemisphere. Over subsequent years, this work, though laborious, led to important scientific discoveries.

Observations made by the Cape astronomers include the first measurement of the distance to a star; the first photographic sky survey; the accurate measurement of the distance to the Sun; developments in stellar spectroscopy; the determination of the shape of the Earth in the Southern Hemisphere; and the first accurate geodetic surveys of Southern Africa.

Measuring stellar distances

A consequence of Nicolas Copernicus's assertion in 1543, that the Earth orbits the Sun, was that

>>

> For much of its history this, the first permanent observatory in South Africa, was the major contributor to positional astronomy in the Southern Hemisphere.

we should be able to observe the apparent shift in the position of the nearest stars from different points in the Earth's orbit. This, however, had not been observed in the centuries following. The reason was, of course, that even the nearest stars are incredibly far away and the effect being looked for is very small.

This led to a "light bulb" moment for Gill as he realised that the positions of stars could now be recorded in quantity on a permanent medium, more reliably than any visual observer could ever hope to do.

When the Royal Observatory was founded in 1820, it was equipped with the most accurate star position measuring devices available. The first believable measurements of this effect, known as "parallax", were made from the Cape in 1831-1833 by Thomas Henderson. By observing the angular "movement" of Alpha Centauri, and knowing the size of the Earth's orbit, this gave the distance to the star by simple trigonometry. Alpha Centauri is still the second-closest star known.

Star surveys by photography

A major occupation of all observatories in the 19th century was making precise observations of star positions one by one and publishing catalogues of these. In 1882, the head of the Royal Observatory, David Gill was surprised by receiving a letter from Mr Simpson, an amateur photographer in Aberdeen, Cape. Simpson had managed to photograph a bright comet that had just appeared but, incredibly, his photographic plates were sensitive enough to register stars in the background.

SAAO

This led to a "light bulb" moment for Gill as he realised that the positions of stars could now be recorded in quantity on a permanent medium, more reliably than any visual observer could ever hope to do. He accordingly set up a special photographic telescope using the largest lens that he could find and set about making the first photographic star catalogue. This was called the Cape Photographic Durchmusterung after its much more laboriously compiled Northern Hemisphere equivalent compiled in Bonn, Germany.

Proxima Centauri

In 1903, the Johannesburg Observatory was established and it achieved its greatest success in 1915 when its Director, Robert Innes, discovered a very faint star near Alpha Centauri. On various grounds he claimed it to be the nearest star to Earth but it took many years of investigation before this could be verified.

The new discovery was named "Proxima Centauri", meaning the nearest in the constellation Centaurus. Not only was it the nearest star but at that time of discovery, it was the least luminous star ever discovered. Other dimmer stars have been found since but Proxima still retains its nearest status and its distance has since been thoroughly verified from space satellites.

Doubling the size of the Universe

In 1948 the private Radcliffe Foundation in the United Kingdom set up in Pretoria what was for a time the largest telescope in the Southern Hemisphere and joint fourth largest in the World. Coincidentally this is a title currently held by the Southern African Large Telescope (SALT).

Early on in the Radcliffe's existence, the then Director, David Thackeray and Adriaan Wesselink, discovered in the Magellanic Clouds a number of RR Lyrae variable stars that astronomers using smaller telescopes could not detect.

In effect, they doubled the size of the Universe! This result was announced to great acclaim at the triennial meeting of the International Astronomical Union in 1952.

By measuring their average apparent brightnesses they determined that the cosmic distance scale originally determined two decades before by Hubble and others was underestimated by about a factor of two. In effect, they doubled the size of the Universe! This result was announced to great acclaim at the triennial meeting of the International Astronomical Union in 1952.

The South African Astronomical Observatory in Cape Town has played a highly significant scientific role over time as the oldest permanent observatory in the Southern Hemisphere. With more than 200 years of history, it still retains its prominence in the international astronomical community.

About the Author:

Dr Ian Glass was born in Ireland and has a BA from Trinity College Dublin and a PhD from MIT. His career in various countries involved X-ray, visual, infrared and radio astronomy. Associated with SAAO since 1971, he has written 6 books and about 220 scientific papers, with over 9000 citations.

SALT:

An ideal astrophysical transient follow-up machine, now and in the future

By David A.H. Buckley and Encarni Romero Colmenero

Caption: SALT preparing for observations at twilight

Growing research into transients amongst South African astronomers

It may seem that, other than for the Moon, planets, meteors and occasional comets, the night sky is essentially unchanging. As astronomers began to observe the sky more closely, and particularly after the invention of the telescope, they observed changes in certain stars' brightness, sometimes slowly and sometimes abruptly, and occasionally new stars which appear and then fade away. These objects are referred to as transients.

These "new stars" were dubbed novae and adapted in combination with other prefixes to describe a wide variety of highly energetic transient phenomena observed in the Universe: *super-novae, hyper-novae and kilo-novae*. These explosive events are powered by a variety of physical processes, from nuclear fusion to gravitational collapse which can create the densest objects in the Universe: neutron stars and black holes.

The study of transients has grown significantly amongst South African astronomers over the last ~5 years or so. In 2016 this led to the first large science programme with the Southern African Large Telescope (SALT). Its aim is to study a variety of astrophysical transients and over 35 collaborators around the world are involved, including graduate students, some who have taken leading roles in various investigations.

> In 2016 this led to the first large science programme with the Southern African Large Telescope (SALT).

In 2018, research into transients in South Africa expanded into the radio domain with the start of the ThunderKAT radio transient programme on the *MeerKAT* telescope array. Since then, both SALT and *MeerKAT* have combined efforts to undertake multi-wavelength observations of a variety of objects, including gamma ray bursts (GRBs), X-ray binaries, cataclysmic variables and active corona stars.

In addition, astronomers have also used international facilities to extend their studies to even higher energies, utilising X-ray and gamma-ray satellites. This year (2020), a new aspect of the SALT programme began with the monitoring of transient Active Galactic Nuclei (the bright compact region at the center of a galaxy), discovered to be undergoing accretion state changes by the *eROSITA* X-ray instrument on the newly launched joint Russian-German *Spectrum Röntgen Gamma* satellite. These are thought to harbour the most massive black holes in the Universe, up to 1010 times the mass of the Sun.

The world of astronomy changed in 2015 with the first ever detection of gravitational waves, predicted ~100 years prior by Albert Einstein. The *LIGO* gravitational wave observatory discovered gravitational waves from two merging black holes, with masses up to ~10 times higher than previously found in accreting binaries. At a total energy dissipation of 1047 Joules, these are ~1000 times more energetic than GRBs, the previous transient record holders in terms of energy output.

On 17 August 2017, the first electromagnetic counterpart of a gravitational wave event was discovered from a kilonova, the result of two neutron stars merging. SALT played a leading role in this discovery, obtaining one of the first optical spectra ever seen of such an event. Since then SALT has continued to search for similar objects during the last joint observing campaign of *LIGO* and its European equivalent, *VIRGO*, which ran up to 23 March 2020, cut short by a month due to the COVID-19 pandemic.

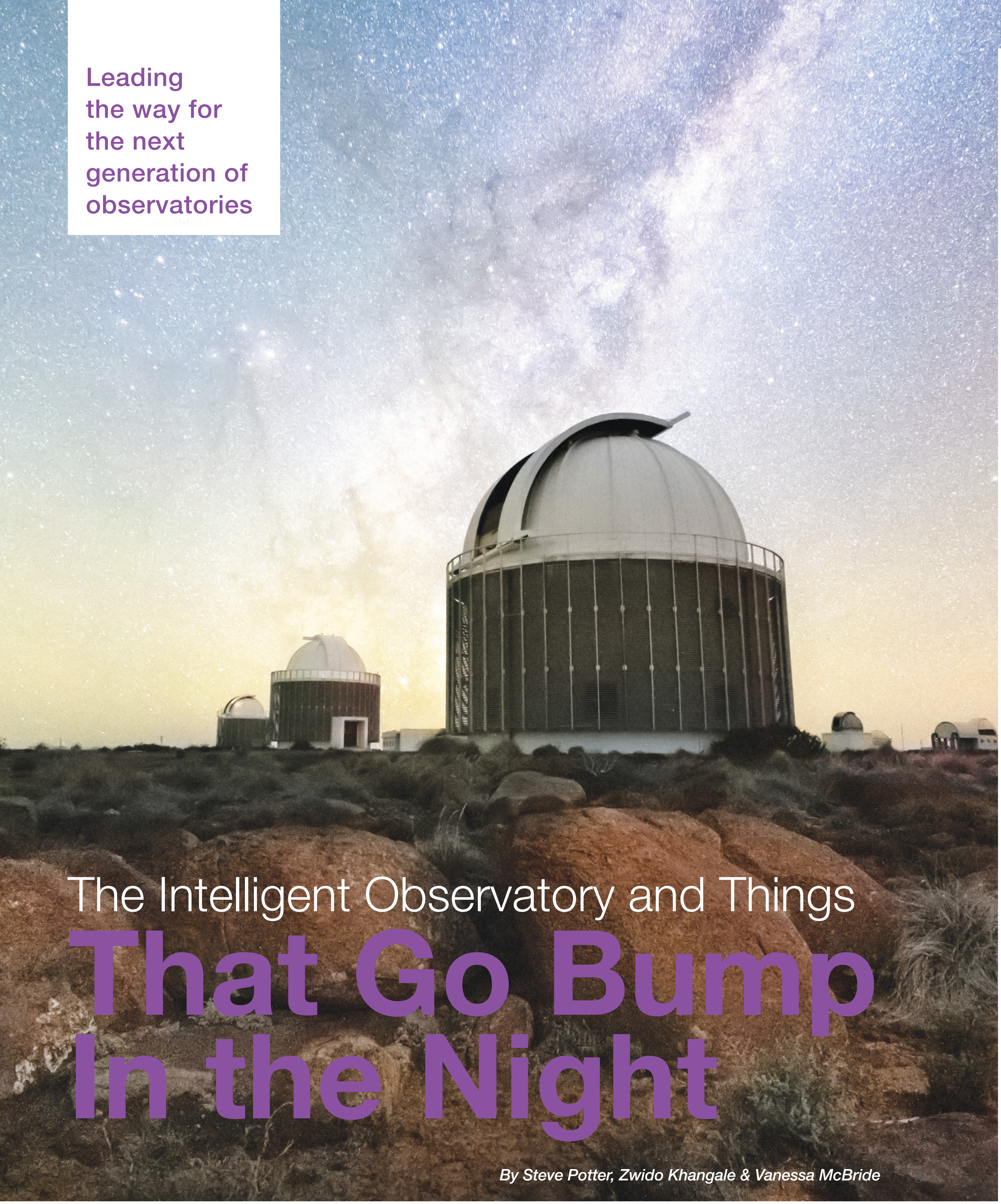
A total of 13 events involving mergers of either two neutron stars or a neutron star and a black hole were followed up by the Zwicky Transient Facility in the USA, together with the parallel GROWTH follow-up network. SALT supported this effort and while a number of supernova transients were discovered serendipitously during this time, no optical counterparts were detected of any of these events by any of the participating telescopes. The next *LIGO/VIRGO* observing runs are expected to begin later in 2021 and again SALT and other SAAO telescopes will be involved.

South Africa is also poised to play a major role in the forthcoming Rubin Observatory Legacy Survey of Space and Time (LSST), which will be a huge game changer in transient detection. This 8m class telescope, currently under construction in Chile, will conduct a 13-year survey of the entire Southern Sky starting in 2023, observing the entire sky every few days. With its huge sensitivity, field of view and speed, it is expected that several million transient or variable objects will be observed every night. Follow-up observations of some of these will be crucial and many telescopes in the Southern Hemisphere will be taking on this task, including SALT. It is planned through provision of rapid SALT follow-up, that researchers in South Africa will gain access to LSST data, software and data products and develop collaborations with the wider LSST community.

About the Authors:

Dr David Buckley was the SALT Project Scientist during the design and construction phase (1998-2005) and then was appointed the first SALT Astronomy Operations manager and SALT Science Director (2005-2015). In 2017 he was appointed as the first SAAO Darragh O'Donoghue astronomer and is currently also serving as SALT Global Ambassador.

Dr. Encarni Romero Colmenero was born in Spain. She has a BSc (Hons) from the University of Southampton and a PhD from the Mullard Space Science Laboratory, which is part of University College London in the UK. She has been associated with the SAAO since 1999 and with SALT from its inception. She was the first ever SALT Astronomer and she is currently the Head of SALT Astronomy Operations.



Leading the way for the next generation of observatories

The Intelligent Observatory and Things That Go Bump In the Night

By Steve Potter, Zwido Khangale & Vanessa McBride

Advances in telescope technology over the last decade have made it possible to monitor the entire night sky on almost a continuous basis. Coupled with affordable computational power and storage, astronomers across the globe are poised to enter a new era of exploring astrophysical transients or, in other words, things that go bump in the night. Some astronomical objects vary slowly while others merge or explode in rapid, bright cataclysmic events which are often detected across the entire electromagnetic spectrum from the radio to the visible to X-rays and even as gravitational waves or neutrino events.

Many sky surveying telescopes are already in operation, with the newest and most ambitious of these, the Legacy Survey of Space and Time (LSST) on the Rubin Observatory, currently under construction in Chile, set to go online in 2024. With so many wide eyes on the sky, the number of these so-called transient events is enormous, perhaps reaching millions per night when LSST comes online. This means that the potential for new discoveries is enormous. Understanding what's behind these transient events requires more detailed follow-up multi-wavelength observations. For example, exploring their spectral signatures or taking high-speed measurements of the more rapid and explosive events.

However, with so many transient events, it is impossible to follow-up even 1% of those expected from LSST alone. Instead the transient events have to be intelligently filtered, classified and the most potentially interesting ones selected for more detailed observations. The South African Astronomical Observatory (SAAO) has embarked on a drive to upgrade all of the telescope facilities on the plateau at the Sutherland observing station to do exactly that.

The new programme, called the Intelligent Observatory (IO), involves the development of software algorithms to filter and to intelligently decide what to observe, and also requires upgrades of the telescopes' hardware so that they become more autonomous and capable of "talking" to each other. Then, given a live-stream feed of alerts from surveys like LSST, the IO will be able to make real-time decisions and subsequently execute a course of follow-up observations that will allow scientists to maximise their understanding of the most interesting objects. This approach catapults a 200-year old observatory squarely into the 4th industrial revolution, with humans and machines working in combination to uncover new results and push the boundaries of our understanding of the Universe.

One such multi-wavelength observation was performed on 06 November 2018 to observe a well studied eclipsing binary system in the constellation of Fornax, known as *UZ For.* We used four telescopes - three in Sutherland: the Southern African Large Telescope (SALT) in spectropolarimetry mode, SAAO 1.9-m telescope and MeerLICHT in photometry mode, and the *MeerKAT* radio telescope.

UZ For was discovered in 1987 as a strong source of X-rays and subsequently classified as a "polar". Polars consist of two stars orbiting each other typically every few hours. The more massive star is the compact remnant core of a sun-like star that has exhausted its hydrogen fuel supply (the white dwarf) and the companion is a low-mass sun-like star. In this setup, the low-mass companion is constantly transferring material to the white dwarf via a ballistic stream.

The white dwarfs in polars are strongly magnetic with field strengths ranging from 10 to 230 million Gauss (the Earth's magnetic field is typically about 0.5 Gauss). Therefore, the transferring material is directed along the magnetic field lines to eventually crash onto the surface near the magnetic poles of the white dwarf, releasing vast amounts of energy seen as X-rays, visible and radio emission.

The two stars in *UZ For* orbit each other every 126 minutes and the system is fortuitously aligned, from our perspective, such that the stars eclipse each other once every orbit. Studying eclipses is very useful for determining basic parameters such as masses and sizes etc, especially because these >>

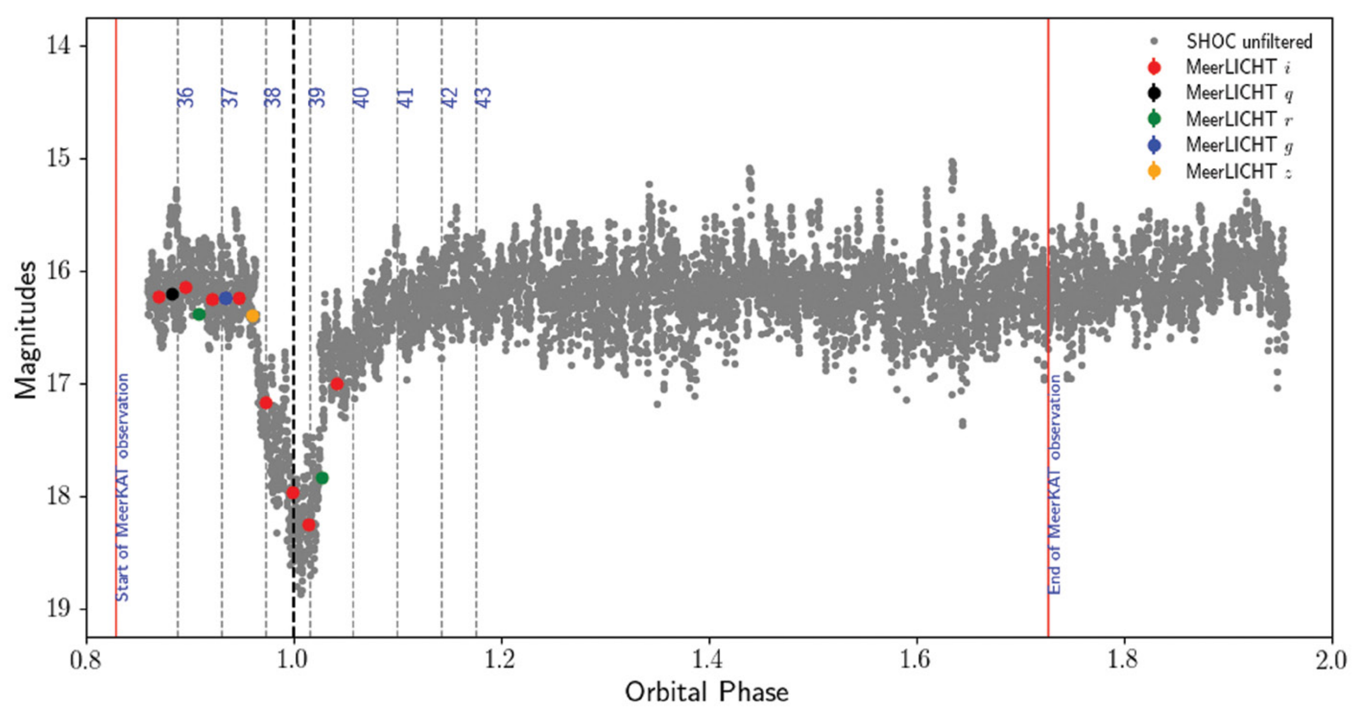


Image caption: The brightness variation of the eclipse of *UZ For*, as seen by four different telescopes in South Africa: *SALT, MeerLICHT, MeerKAT* and the *SAAO* 1.9m telescope.

systems are too far away to resolve the individual stars.

The high-speed measurements of the brightness variations (using the SAAO 1.9m telescope) shows the eclipse of the white dwarf by the companion in *UZ For*. Additional colour information was obtained with the MeerLICHT telescope and is overlaid around the eclipse (see Figure below). The SALT observations (dotted grey lines) as well as the start and end-time of the *MeerKAT* radio observations (red lines) are also shown. Analysis of the SALT spectropolarimetric observations revealed that the light from *UZ For* is circularly polarised, a typical characteristic of light that is produced in regions of strong magnetism. Detailed modelling of the SALT spectrum suggests that the magnetic field strength of the white dwarf in *UZ For* is 57 million Gauss. The *MeerKAT* radio observations also confirmed the presence of radio emission, the origin of which is still under debate.

This was the first time that these four South African telescopes were used in conjunction to observe an astronomical target. It required months of planning and communication to organise such synchronous observations. In future, the IO will make observations like these a more common occurrence. The IO will set a new benchmark for efficient follow-up of things that go bump in the night, one that is led by South Africa and will likely be emulated by observatories across the world.

About the Authors:

Originally from the UK, Prof. Stephen Potter obtained his PhD from University College London. His career with SAAO began in 1999 where he is now Head of Astronomy and holds a visiting professorship with the University of Johannesburg. His research expertise is in observational astronomy particularly of high-energy galactic objects.

Assoc. Prof Vanessa McBride is an astronomer at the IAU's Office of Astronomy for Development and Head of Research at the South African Astronomical Observatory. She is also an adjunct associate professor in the Department of Astronomy at the University of Cape Town.

South Africa's MeerKAT Telescope Provides a New Window into Galaxy Evolution

By Sarah Blyth and Imogen Whittam

Gaining new understanding of the Universe with the most powerful radio telescope in the Southern Hemisphere

MEERKAT IMAGES: HTTPS://WWW.SARAO.AC.ZA/GALLERY/

Compared to the long history of optical astronomy facilities in South Africa, the establishment of radio astronomy in South Africa is much more recent. Beginning in the 1970s with what later became the Hartebeesthoek Radio Astronomy Observatory (HartRAO), South Africa today hosts one of the largest and most sensitive radio telescope arrays in the world: the *MeerKAT* telescope. The motivation for the telescope was South Africa's ultimately successful bid for hosting the Square Kilometre Array (SKA) telescope and therefore *MeerKAT* is known as an SKA 'precursor' instrument and falls under the South African Radio Astronomy Observatory (SARAO).

Inaugurated on 13 July 2018, *MeerKAT* is a radio interferometer consisting of 64 dishes, each 13.5m in diameter with the longest distance between two antennas being 8km. It will feature three receiver bands providing very broad access across the radio spectrum. The telescope is situated in one of the most radio-quiet locations on Earth in the Karoo in the Northern Cape province, beautifully complementing the better-than-specified sensitivity of this proudly South African facility. In the longer term, *MeerKAT* will form the core of the much larger SKA facility which will soon start construction.

MeerKAT's excellent capabilities enable a broad range of science topics to be explored with the telescope. The observing time is primarily dedicated to several large surveys, with observing times greater than 1000 hours each. The remainder of the time will be allocated to smaller projects. The large surveys range from studying compact objects including black holes, and stellar remnants such as pulsars and white dwarfs, up to the much larger scales of galaxies and galaxy clusters. Two such *MeerKAT* large galaxy evolution projects are the LADUMA and MIGHTEE surveys.

Understanding how galaxies form and how they change with time is one of the key challenges of modern astrophysics. While a huge amount of progress has been made in recent years, there remain some crucial unanswered questions, for example: what affects how quickly the stars form in the galaxy? How does the supermassive black hole at the centre influence the galaxy? How do galaxies exchange matter and energy with their environments and how do they grow in mass over time? With its exquisite imaging capabilities, *MeerKAT* has the potential to provide a big step forward in our understanding of the life-cycles of galaxies, including our own Milky Way.

Radio observations provide a unique window into the processes that occur within galaxies. Emission at radio wavelengths is produced in various mechanisms including star formation and energetic processes related to the central black hole (known as an "active galactic nucleus"). Neutral atomic hydrogen gas (HI), a major component of galaxies and the raw fuel for star-formation, also emits a radio signal with a characteristic wavelength of 21cm.

One can think of the MIGHTEE and LADUMA surveys as tiers of a wedding cake: MIGHTEE covers a bigger, shallower area on the sky, while LADUMA is observing only a single patch of sky covering roughly one square degree, but to a great depth. For MIGHTEE, the telescope will observe four different regions of the sky covering a total of 20 square degrees. Researchers will use these images, together with data from other wavelengths such as optical and infrared, to investigate cosmic magnetism; the star formation history of galaxies; and the growth of black holes over time. The unique combination of very deep radio observations over a relatively large area mean that MIGHTEE provides an exciting opportunity to significantly improve our understanding of how galaxies form and evolve with time.

So far, about 400 hours of MIGHTEE observations have been taken and researchers are in the process of publishing the first set of results. It is early days but surprises are already being found, for example "giant radio galaxies" - the largest single structures in the Universe - seem to be more common than previously thought.

To gain a better understanding of how galaxies have evolved over cosmic time, it is also vital to make a census of the gas (which provides the fuel for star formation) in galaxies at different epochs. The wide range in radio frequency coverage combined with the excellent sensitivity of *MeerKAT* will enable us to observe the emission from HI far beyond the local Universe out to much greater distances (and look-back times) than has previously been possible with current radio telescopes.

MIGHTEE will observe hydrogen gas in galaxies over the past 5.5 billion years and LADUMA will probe even further back in time, observing galaxies as they were nine billion years ago, using roughly 3000 hours of observing time with MeerKAT. With the data collected, scientists are aiming to investigate the evolution of the gas content of galaxies over two-thirds of the age of the Universe. Since the HI signal is very weak, HI measurements of distant galaxies require long observing times. Both the MIGHTEE and LADUMA surveys are currently in progress and looking forward to publishing early HI results soon.

Galaxy evolution is just one of the many research areas where *MeerKAT* is producing exciting new results. With more than 30 scientific papers based on *MeerKAT* data covering a wide range of topics already published, this new instrument is already making a splash in the international science community.

About the Authors:

Dr Imogen Whittam is a Hintze Fellow at the University of Oxford where she researches radio galaxies. She has a PhD in astrophysics from the University of Cambridge, and spent five years working as a SARAO Postdoctoral Fellow at the University of the Western Cape. She currently co-chairs the MIGHTEE continuum science working group.

Assoc. Prof Sarah Blyth is an Associate Professor in the Department of Astronomy at UCT. Her research focus is on studying galaxy evolution using multi-wavelength data, with a particular focus on the role of hydrogen gas. She is a principal investigator of the *MeerKAT* Large Survey Project, LADUMA, and the UCT co-director of the National Astrophysics and Space Science Programme (NASSP).

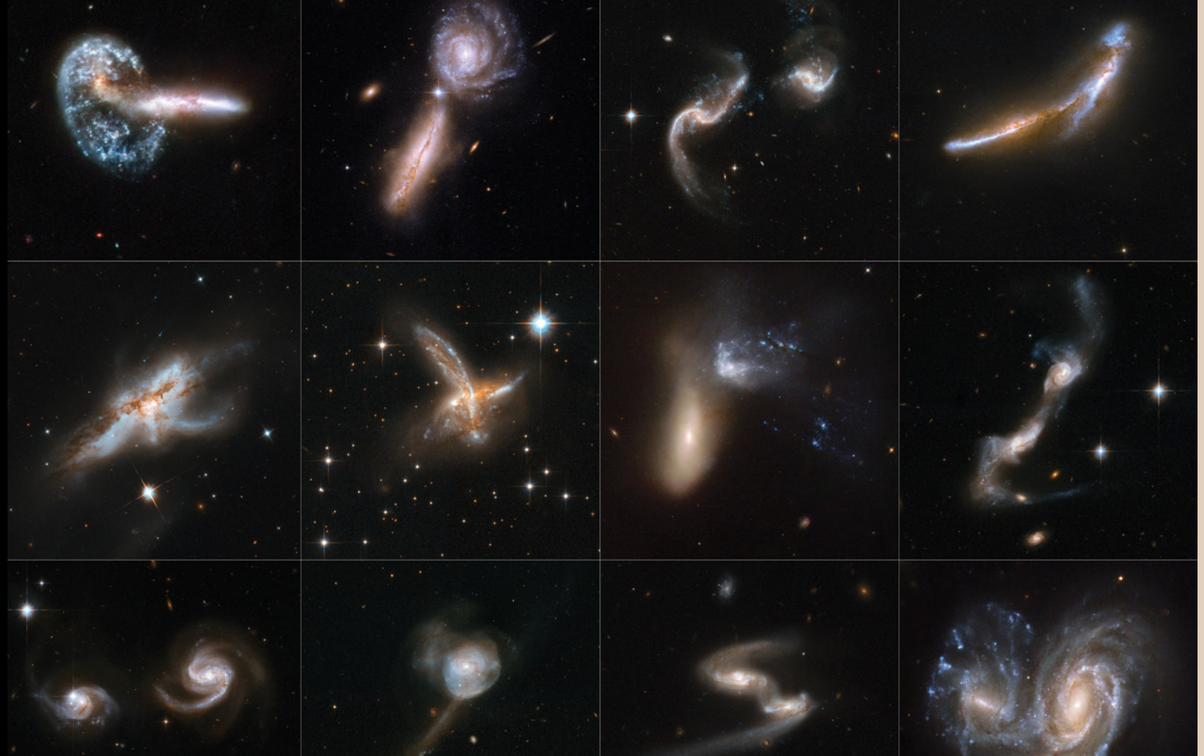


Figure 1. A collection of interacting galaxies by the Hubble Heritage Team. *Copyright: NASA/ ESA/ STScI/AURA (The Hubble Heritage Team) - ESA/Hubble Collaboration/ University of Virginia, Charlottesville, NRAO, Stony Brook University (A. Evans)/ STScI (K. Noll)/ Caltech (J. Westphal)*

NO GALAXY IS AN ISLAND:

The effects of environment on galaxy evolution

By Zara Randriamanakoto and Rosalind Skelton

Revealing the complex interactions of galaxies

There are billions of galaxies in the visible Universe beyond our home galaxy, the Milky Way. Galaxies come in different shapes and sizes, and are made up of gas, dust, black holes, dark matter and billions of stars. Observations have shown that galaxies may be isolated, members of a small galactic conglomerate or huge groups, known as galaxy clusters. Galaxy clusters may themselves cluster together into superclusters, the largest structures in the Universe.

There is mounting evidence that a galaxy's star formation activity and its evolution are influenced by the surrounding environment, regardless of the type of community in which it resides. Galaxies do not evolve in isolation, but are strongly affected by interactions with other galaxies. Some galaxies show slight distortions from the gravitational pull of nearby neighbours. Others have faint streams of stars and gas around them, signalling that they have cannibalised smaller dwarf systems over billions of years. The most extreme examples of galaxy interactions are completely disrupted systems that have clearly been involved in major head-on collisions. Figure 1 shows examples of interacting galaxies observed by the Hubble Space Telescope.

How exactly does the environment affect both star formation and galaxy evolution? This is one of the most active areas of extragalactic astronomy research in South Africa, addressing a key question in understanding our Universe. To tackle this, astronomers in South Africa use telescopes within South Africa and around the world to observe the electromagnetic radiation emitted by galaxies at different wavelengths.

Stars and star clusters produce light from the ultraviolet through to the visible and near infrared. Gas within galaxies is mostly made up of cool neutral hydrogen, which emits radio waves at a wavelength of 21cm. The hot gas that surrounds galaxies in groups and clusters produces much higher energy radiation, observed as a halo of X-rays.

At the centre of most galaxies lies a supermassive black hole. Although no light escapes from the black hole itself, the bright accretion disks that form around them as they pull in material emit across a range of wavelengths. Active black holes may also produce giant jets that can be observed in the radio.

By observing the full electromagnetic spectrum we learn about each of these components and the physical processes going on within galaxies at different scales. Long wavelength radio waves are captured by radio dishes such as the *MeerKAT* array, while visible light can be seen by optical telescopes such as SALT. For example, Figure 2 shows an optical image of galaxies in the Fornax galaxy cluster. We gain information on where the gas is in this cluster by overlaying contours from *MeerKAT* radio observations.

High energy ultraviolet light and X-rays require space telescopes above the Earth's atmosphere to be observed. The radiation from very distant galaxies takes a long time to reach us because it must travel through space at the cosmic speed limit; the speed of light. We see the galaxies as they were in the past, when they emitted that light. This enables us to piece together how populations of galaxies have changed over time by looking at galaxies at different distances from us, and therefore at different cosmic epochs.

A recent study of nearby galaxies, led by scientists at the South African Astronomical Observatory, found that the extreme environments within interacting galaxies are where young, massive star clusters are most likely to form. These highly compact stellar nurseries are the most massive regions of newly formed stars in galaxies.

Normal spiral galaxies form relatively few of these exotic star clusters. By comparing the star formation in interacting and isolated galaxies, and combining with statistical studies, we can observe subtle differences, with galaxies in pairs having a wider range of star formation rates than similar isolated galaxies.

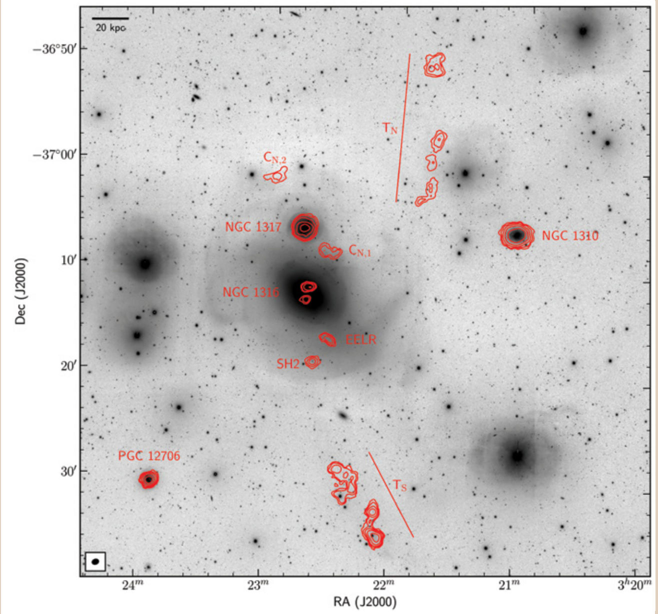


Figure 2. An optical image of galaxies in the Fornax cluster of galaxies, with contours from the *MeerKAT* radio telescope showing where neutral hydrogen is found. (Image credit: Serra et al. 2019, Astronomy & Astrophysics 628, A122).

The field of extragalactic astronomy is constantly pushing boundaries to explore the mysteries of the Universe. Thanks to South African-based telescopes such as SALT and MeerKAT, local astronomers are quantifying how environment affects galaxies as they evolve.

About the Authors:

Dr Zara Randriamanakoto is a postdoctoral researcher at the SAAO. She received her PhD in Astronomy from the University of Cape Town focusing on multi-wavelength observations of young massive star clusters and the search for dying radio galaxies. She is also passionate about science communication.

Dr Rosalind Skelton is a support astronomer for SALT at SAAO. She has a PhD in galaxy formation and evolution from the University of Heidelberg (Max Planck Institute for Astronomy) and did postdoctoral research at Yale University and SAAO before joining the SALT team.

Caption: Artist's impression of a massive star interacting with a neutron star.

Dancing WITH THE STARS

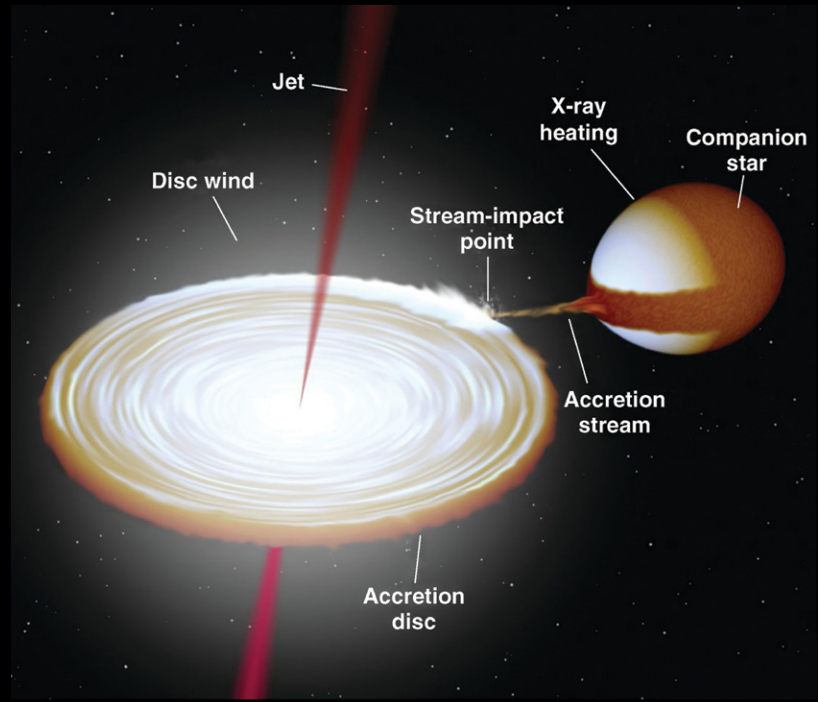
By Itumeleng Monageng and Shazrene Mohamed

Observing the "stellar tango" between pairs of stars

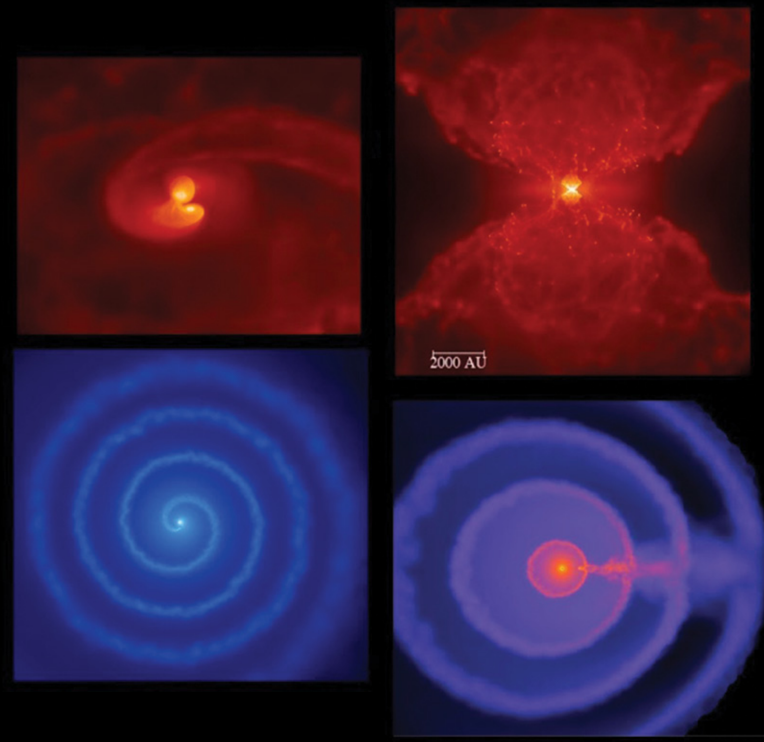
Stars are a major keystone for understanding structures at all scales in the Universe; from galaxies hundreds of thousands of light years across to planets and even life. Heavy elements such as carbon, nitrogen and oxygen are produced by the nuclear furnaces in their cores and ejected into galaxies by powerful stellar winds and explosions. Astronomers use stars to trace the complex historical interactions of galaxies; to investigate extreme physical processes that cannot be recreated on Earth; and the brightest stellar explosions are used in cosmology to obtain clues about the origin and fate of our Universe.

Stellar astrophysics dominated early astronomy (see I. Glass, this issue) with South Africa leading more recent studies of pulsating, cool giant stars. As the resolution of telescopes improved, we learnt that, unlike our solar system that contains only one

ESA/ADES MEDIALAB



Caption: Artist's impression of gas from a companion star accreting onto a black hole.



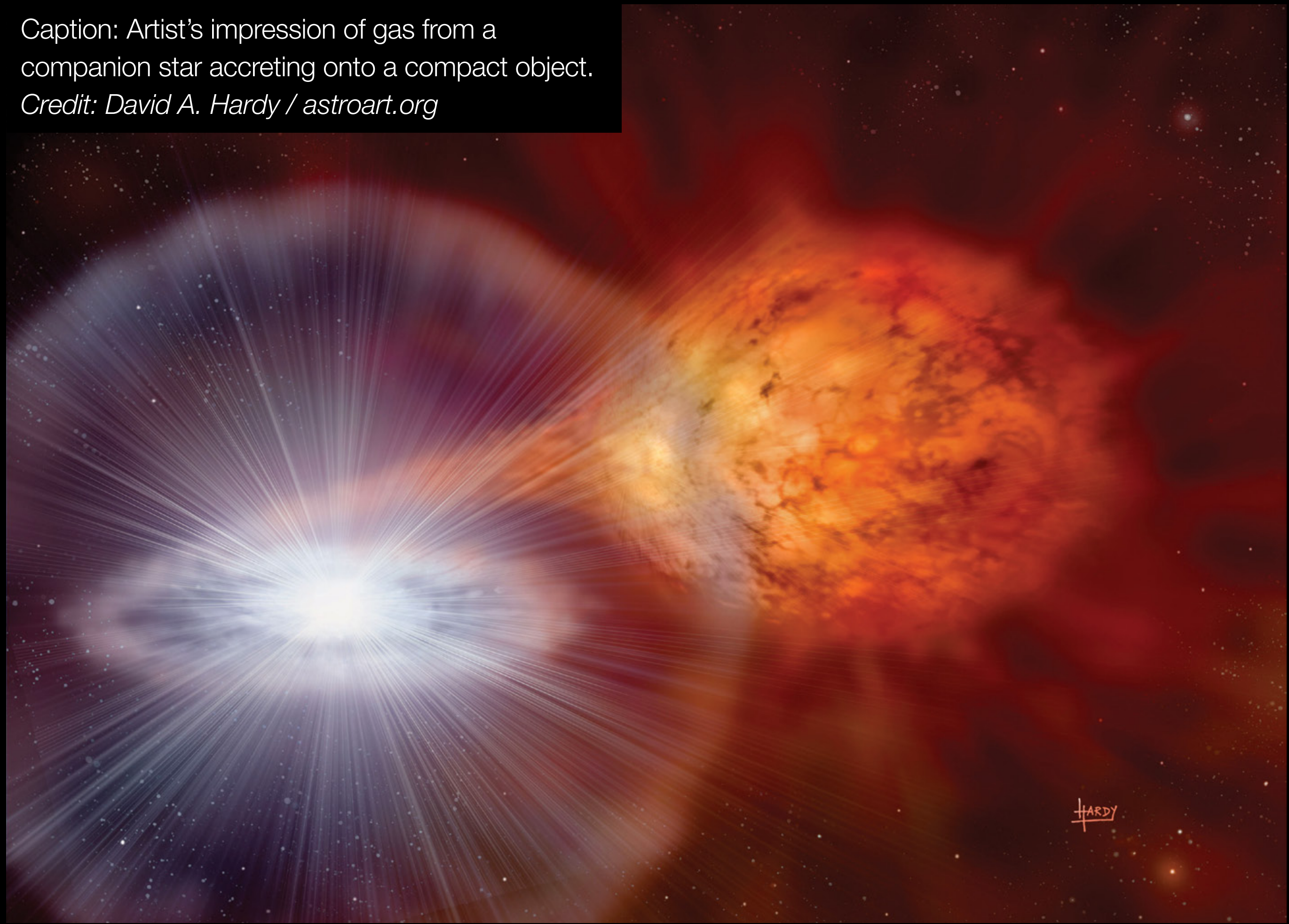
Caption: Simulations of interacting stars by A/Prof Shazrene Mohamed.

star, the Sun, a large fraction of the stars we see in the night sky are in multiple systems. A majority of these stars are in pairs (binary systems) and orbit around a common centre of mass. In systems where the separation between the stars is large (so called wide binaries), the stars evolve essentially like isolated, single stars. In close binaries, however, there is significant interaction, often with the transfer of mass and angular momentum between the two stars. This "stellar tango" can dramatically affect the evolutionary paths of these stars. It can extend or shorten their lifetimes and produce high energy radiation, outbursts and explosions.

The type of interaction and its consequences depends on the size of the orbit and the nature of the two stars - generally one acts as a matter donor and the other an accretor. Roche-lobe overflow occurs when the donor star fills the volume of space around it within which material is gravitationally bound to it. Wind accretion occurs when the donor star has a substantial wind with high velocities (much larger than the escape speed of the star), a small fraction of which is accreted by the companion in its orbit. In disc accretion, the matter can be captured by the companion from a disc around the donor star.

Identifying the stellar components and which of these "dances" is at play is key to understanding the nature and evolution of binaries. Systems containing a white dwarf accreting matter from a low-mass donor star are classified as cataclysmic variables or symbiotic binaries. If the accretor is a neutron star or black hole, a large portion of the emission is observed at X-ray wavelengths; there are two main classes: in cases where the donor star has a mass similar to that of the Sun or less, these fall under the subclass of low-mass X-ray binaries, while high-mass X-ray binaries have donor stars with masses 10 times that of the Sun or more. While some of the binary interactions result in stable, steady emission from the systems, others result in highly energetic and sometimes catastrophic explosions (see S. Potter, Z. Khangale & V. McBride, this volume).

SAAO telescopes are used to explore some of the mysteries surrounding these binary stars. Optical spectroscopy, a technique used for splitting light into different wavelength components, can be used to determine the chemical composition of stars' atmospheres. The unique signatures in their spectra are used to classify them, and from the subtle shifts>>



Caption: Artist's impression of gas from a companion star accreting onto a compact object. *Credit: David A. Hardy / astroart.org*

of the spectral lines we determine important parameters such as the orbital periods; the geometries of the orbits; and the masses of the stars. The latter is particularly important in distinguishing between neutron star and black hole accretors.

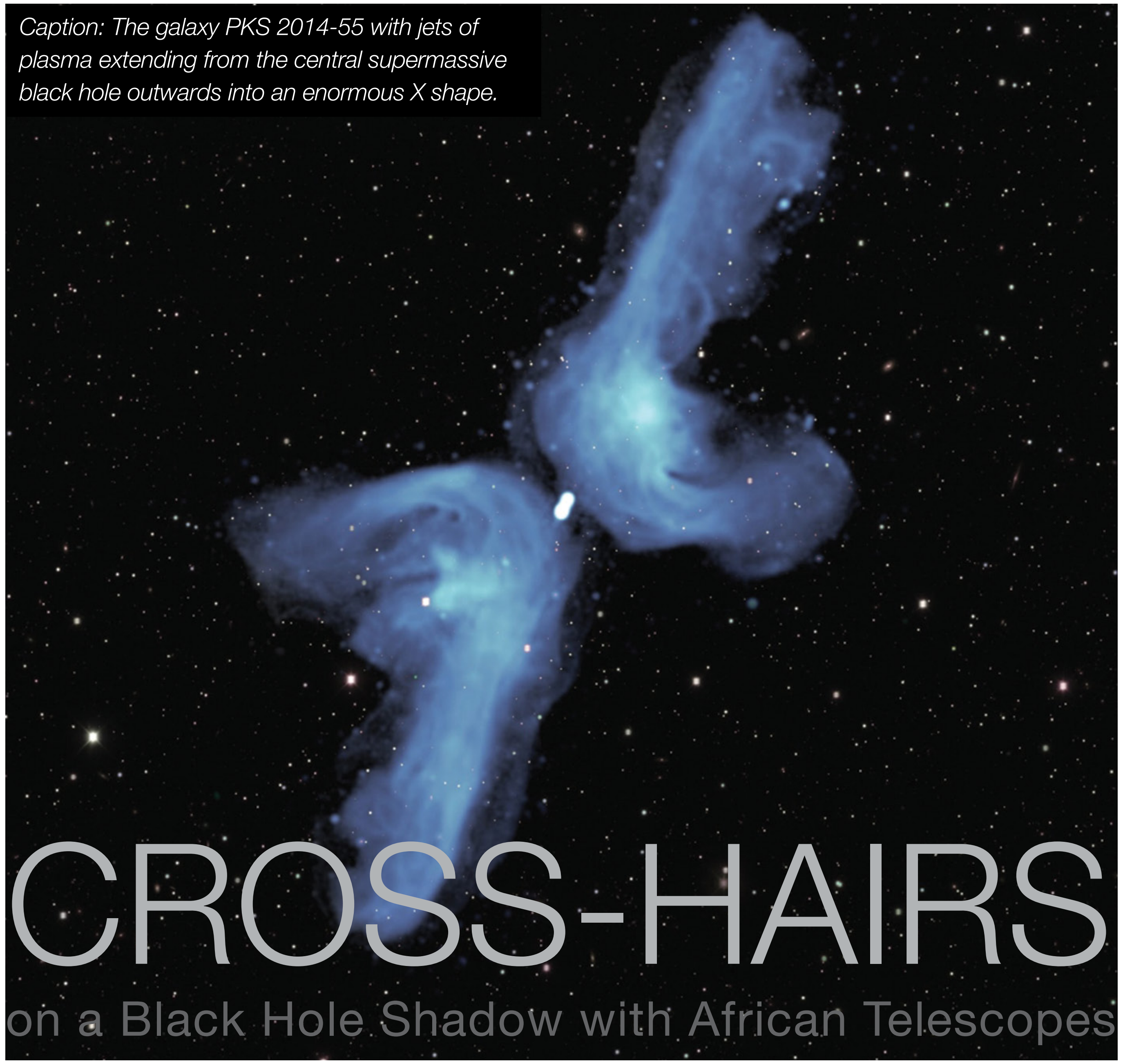
We also use data at radio, infrared, UV, X-ray and gamma-ray wavelengths to obtain a complete picture of the processes taking place. Analytic and 3D supercomputer models are used to test our understanding of the systems and give us clues to the formation, evolution and final fate of the binaries.

South Africa is well-placed to conduct multiwavelength studies of binary stars, with leading researchers in this field making use of flagship facilities such as SALT and more recently the *MeerKAT* radio telescope, as well as future facilities such as the Vera Rubin Observatory. Through these observations, together with our simulations and analytic models, we will continue to choreograph our dance with the stars, improving our understanding of the Universe and our place in it.

About the Authors

Dr Itumeleng Monageng received his PhD from the University of Cape Town (UCT) in 2018. He currently holds a joint position between the South African Astronomical Observatory and UCT where he conducts research that focuses on the study of X-ray binary stars using multiwavelength facilities, including SALT and MeerKAT.

Assoc. Prof Shazrene Mohamed is an astrophysicist at the SAAO and UCT. Her research focuses on supercomputer models of stars and their interactions with nearby companions. She received her A.B. from Harvard and PhD from Oxford. She is an NRF P-rated researcher and UCT VC 2030 Future Leader.



Caption: The galaxy PKS 2014-55 with jets of plasma extending from the central supermassive black hole outwards into an enormous X shape.

CROSS-HAIRS

on a Black Hole Shadow with African Telescopes

By Roger Deane and Kshitij Thorat

Shedding light in the darkest places

One of the most pressing research themes in contemporary astrophysics is the nature of black holes; how they form relativistic jets; and their relationship to the gas and stars in their host galaxies. As in many disciplines, from medical science to psychology, we push to the extremes to better understand where our theories break down in order to gain new ground and improve our models of nature.

One way this is done in astrophysics is to seek out exotic cosmic objects that signify some strange event, class, or anomaly which can, in turn, be used as a laboratory in its own right. By seeking out strange and special cases of the emission associated with black holes, we can (metaphorically) shed light on these intrinsically dark objects.

Over the past 18 months, several South African-based researchers were part of two high-visibility >>

SAAO

1. South Pole Telescope **2.** Atacama Large Millimeter/submillimeter Array and Atacama Pathfinder Experiment (Chile) **3.** Large Millimeter Telescope (Mexico) **4.** Submillimeter Telescope (Arizona) **5.** James Clerk Maxwell Telescope and Submillimeter Array (Hawaii) **6.** IRAM 30-meter (Spain)

Caption: The positions of the telescopes which comprise the Event Horizon Telescope.

results that revealed extraordinary radio images. While not directly related to one another, they serve as informative and exciting examples of exotic radio morphologies that can teach us about black holes and their environments.

The first example was enabled by the Event Horizon Telescope (EHT). The EHT combined signals from several large antennas across the globe (see Figure) to synthesise a single Earth-sized telescope. The EHT Collaboration achieved their primary objective in April 2019 when they unveiled the first ever image of a black hole.

This image of a black hole is fundamental to our understanding of the nature of gravity. By zooming right into the ring-like emission around the black hole in a galaxy 55 million light years away, we can measure the local space-time distortion. Comparing this ring size and shape with what different theories of gravity predict enables a brand new, extreme test of this fundamental force. In addition, the unparalleled sharpness of the EHT images, especially of the magnetic field structure, helps unveil how black holes launch jets at speeds close to that of light.

On the opposite end of the scale to the EHT's "zoomed-in" black hole image, the second example, announced in May of 2020, is a majestic new image of the entire galaxy PKS 2014-55. PKS 2014-55 is an astronomical object which emits radiation in radio waves. This image was taken by *MeerKAT*, which is South Africa's powerful new radio telescope in the Northern Cape.

Objects such as PKS 2014-55 are powered by supermassive black holes which launch jets to vast distances. What is unusual about PKS 2014-55 is that rather than having a shape dictated by the direction of these jets, it has an additional axis, forming an "X" on the sky.

One explanation for the unusual shape of PKS 2014-55 is the merging of supermassive black holes at the centre of the "host" galaxy. Therefore, galaxies like these can be important signposts of the evolutionary life-cycle of black holes, despite the fact that they exist on scales far larger than that of the black holes themselves. This provides information on how the black hole jets interact with

SAAO

Caption: The image of a black hole as captured by the Event Horizon Telescope

the edges of a galaxy on scales of millions of light-years.

The telescopes that generated these two iconic images, *MeerKAT* and the Event Horizon Telescope, are very different instruments with very different goals. However, both telescopes rely on a Nobel-prize-winning technique called radio interferometry, which is able to stitch together multiple antenna data streams so that they can act as a single virtual telescope tuning into the symphonies of the universe.

In the case of *MeerKAT*, there are 64 antennae within an 8km region in the Karoo. In the EHT case, there are around 10 different stations (a growing number) spread across four continents with separations up to 10,000 km. An apt comparison between *MeerKAT* and the EHT is that of a hand-held wide-field camera and an electron microscope, respectively. Both are able to image exotic radio morphologies (shapes), but on vastly different scales.

While the EHT could make out a doughnut on the lunar surface, *MeerKAT* would barely be able to tell Johannesburg and Pretoria apart if they were on the moon. However, *MeerKAT* is able to image a wide area of sky, detecting thousands of objects simultaneously, all with superb imaging quality, albeit at a lower sharpness than the EHT.

Another way you could think of the two telescopes is that *MeerKAT* is able to identify needles in a haystack by surveying large swaths of sky at great depth. In contrast, Earth-sized telescopes such as the EHT and the eventual African VLBI Network are able to make detailed studies of those needles.

In the pursuit of studying exotic radio morphologies, great effort is being put into developing new antennae in new sites, including Africa, to improve the imaging quality of black holes and their "shadows". *MeerKAT* is also being enhanced with an extra 20 antennae to become *MeerKAT+*; and then with a further 113 antennae to become the first phase in the Square Kilometre Array's mid-frequency component.

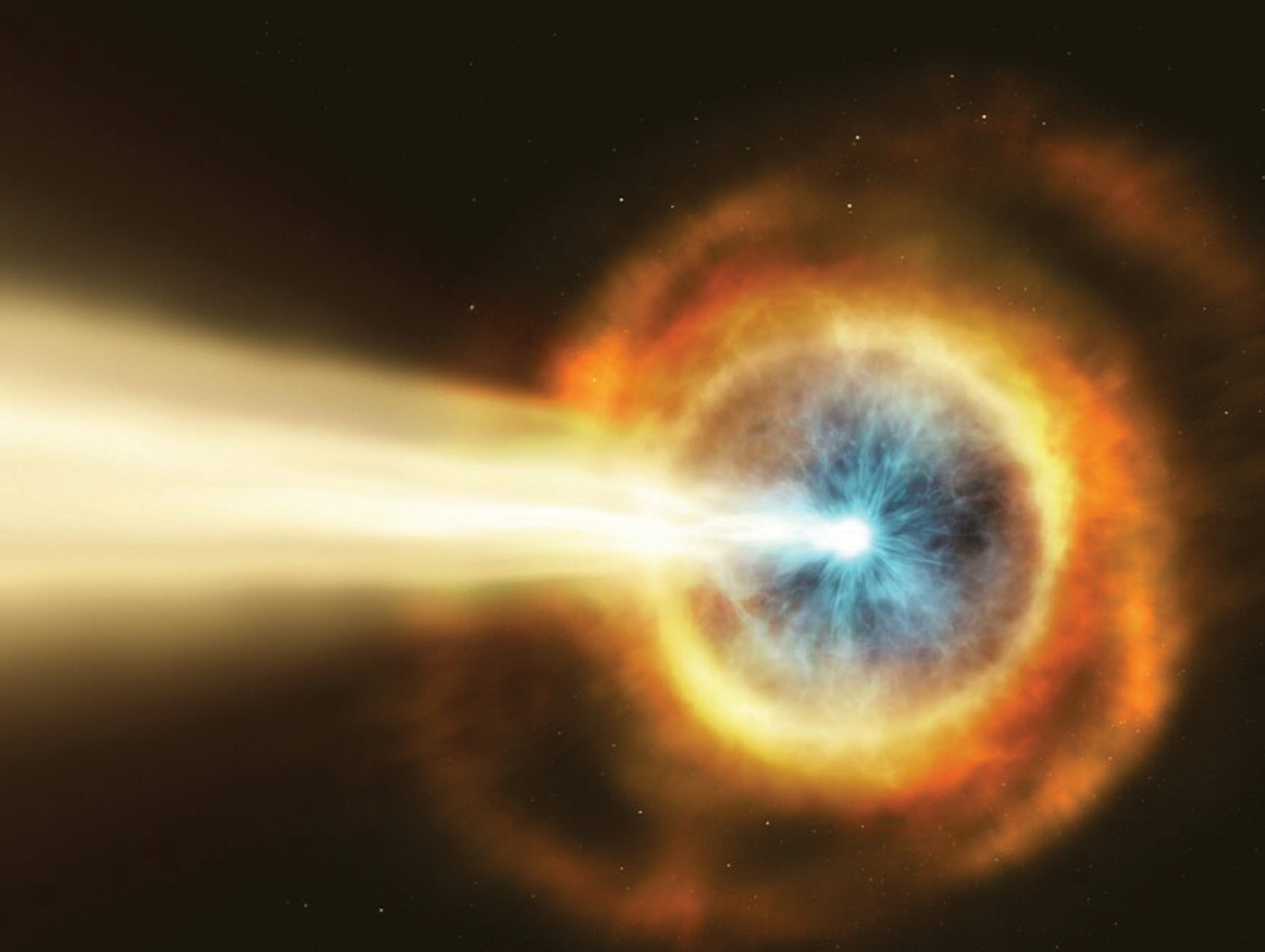
Despite the enormous successes, the *MeerKAT* and EHT telescopes are in many ways just getting started. The EHT's near-term goals include the challenge of turning 'mere imagery' into black-hole movies, as well as making precision measurements of the size and shape of the black hole at the centre of our own galaxy.

The ring-like and X-shaped images profiled here are just visually enchanting examples of what will be a rich tapestry of important scientific advances made by these cutting-edge telescopes built entirely or partially on African soil, and using hardware and software developed by researchers on the African continent.

About the Authors:

Assoc. Prof Roger Deane is the SKA Chair in Radio Astronomy at Wits University and an Extraordinary Professor at the University of Pretoria. His research interests cover a broad range of energy and spatial scales using the power of next-generation radio telescopes such as *MeerKAT* and the Event Horizon Telescope.

Dr Kshitij Thorat works as a postdoctoral fellow at the University of Pretoria. He finished his doctoral work at the Indian Institute of Science, after which he has been based in South Africa. His research interests revolve around extragalactic radio sources: their life-cycles, morphology and their impact on surroundings.



Gamma-Ray Astronomy, H.E.S.S., and Gamma-Ray Bursts

By Markus Böttcher, Lenté Dreyer, Cornelia Arcaro

Detecting the most powerful events in the Universe

Gamma-rays constitute the most energetic form of radiation, carrying up to trillions of times the energy of visible light, and probe the most violent processes in the Universe – for example, in the vicinity of black holes, rapidly spinning stars, and supernova explosions. The highest-energy gamma-rays and cosmic rays observed thus far indicate that natural processes in the Universe are able to accelerate elementary particles to energies that are billions of times higher than the most powerful man-made particle accelerator, the Large Hadron Collider at CERN, can achieve.

Figure 1: The H.E.S.S. telescopes near Windhoek, Namibia

SAAO

Figure 2: Artist's impression of a long gamma-ray burst in progress. Credit: NASA Goddard Space Flight Center.

Like most forms of radiation (except radio waves and visible light), gamma-rays are absorbed in the Earth's atmosphere, so one can't simply build a telescope on the ground and observe the gamma-rays directly. The highest-energy gamma-rays detected so far have more than 100 billion times the energy of visible light and are known as "very-high-energy" (VHE) gamma-rays.

Even though these VHE gamma-rays are absorbed in the atmosphere, they have enough energy to create a shower of secondary particles along their initial direction of travel. These secondary particles emit "Cherenkov light" which can be imaged with ground-based telescopes.

The shower image tells astronomers where the gamma-ray came from, and the total Cherenkov light in the shower is a measure of the photon's energy. The High Energy Stereoscopic System (H.E.S.S. – see Figure 1) in Namibia is the largest telescope facility in the world specialising in the detection of these particle showers.

H.E.S.S. is operated by an international collaboration of about 250 scientists in 13 countries, including the University of Namibia, as well as North-West University, Wits University, and the University of the Free State in South Africa.

The large, central telescope of H.E.S.S. (28m primary mirror diameter), is the latest addition to the array (inaugurated 2012), and was specially designed to be able to move rapidly from one sky position to another. The reason was a decade-long hunt for the VHE gamma-ray signatures of gigantic cosmic explosions called gamma-ray bursts (GRBs). >>

Long GRBs (lasting several seconds to minutes) are caused by the violent explosions of very massive stars (likely more than 25 times more massive than our sun) at the end of their lives. When these stars have used up most of their nuclear-burning fuel, their core collapses to form a black hole which gradually swallows part of the star's gas and ejects streams of gas flowing out at almost the speed of light (see Figure 2). Gamma-rays from GRBs of much lower energies than accessible to H.E.S.S. had already been detected in the 1960s.

Long GRBs (lasting several seconds to minutes) are caused by the violent explosions of very massive stars (likely more than 25 times more massive than our sun) at the end of their lives.

The prompt GRB phase is followed by a slowly decaying afterglow, detected from radio waves to X-rays. Many theories predicted that some GRBs might also emit VHE gamma-rays, detectable by Cherenkov telescopes. Since GRBs occur unpredictably at random positions in the sky, the H.E.S.S. collaboration developed a sophisticated strategy to redirect the telescopes as quickly as possible to the position of newly detected GRBs, in some cases within only one minute of the GRB alert. Over the course of half a decade, though, all such attempts proved unsuccessful.

The breakthrough came when H.E.S.S. responded to a GRB on 20 July 2018, called GRB 180720B. The burst occurred during daytime at the H.E.S.S. site, when the telescopes are not operational. The afterglow phase of the GRB, however, was observed by North-West University postdoc Cornelia Arcaro at the H.E.S.S. site, but only about 10 hours after the burst. The team was not very optimistic, since most theorists had expected that H.E.S.S. would have the highest chance of a VHE gamma-ray detection only during the first few minutes. However, careful analysis of the data taken that night revealed a significant signal and thus the first successful detection of a GRB afterglow in VHE gamma-rays.

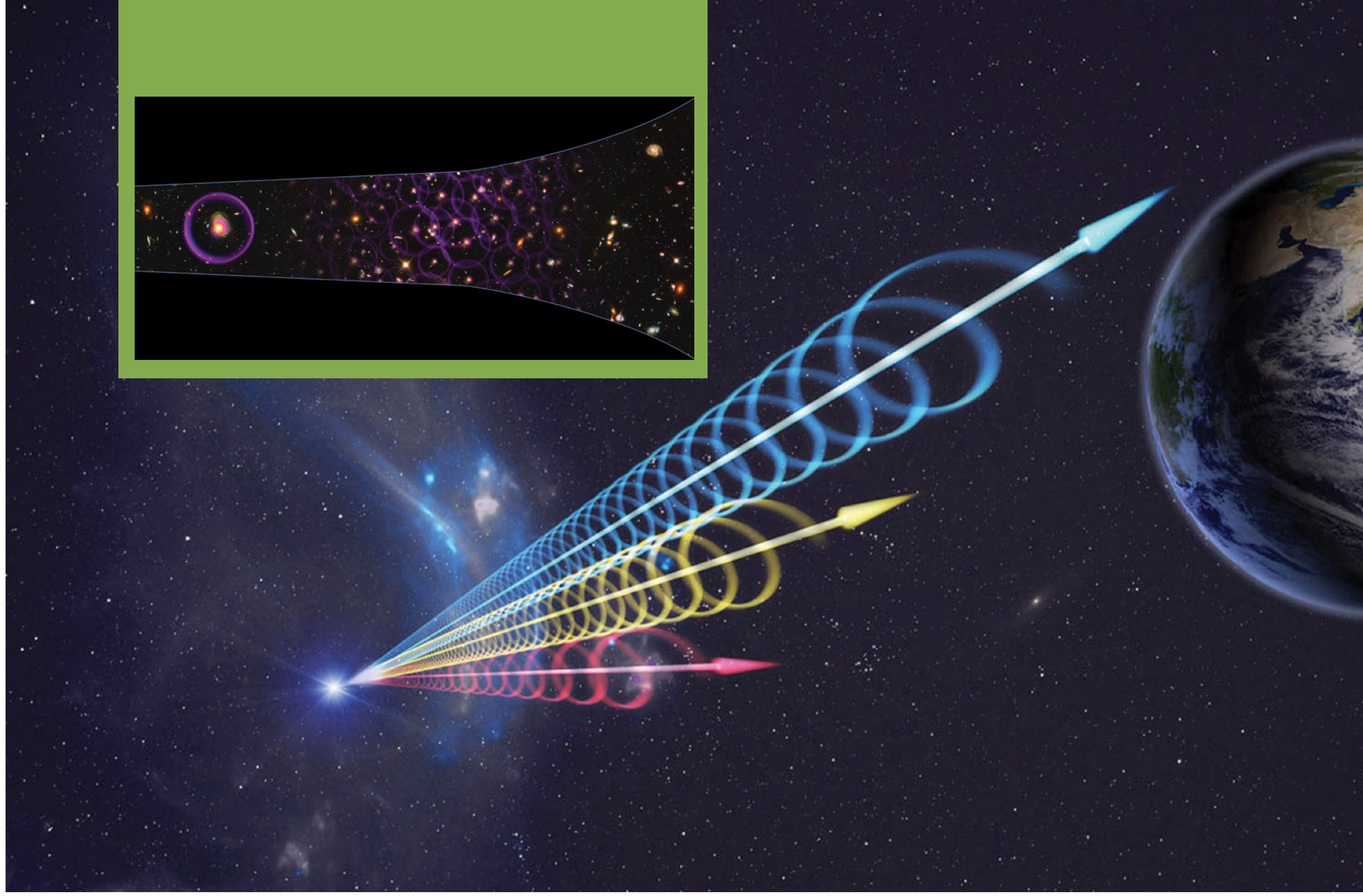
The results were published in Nature in November 2019 (Nature 575, 464). They demonstrated that even several hours after the burst, when the ejected material in the jets is slowing down, particles are still being accelerated to extremely high energies. H.E.S.S. detected another GRB afterglow last year (on 29 August 2019) initially four hours after the initial GRB, and again the next day, thus establishing that some GRBs are violent particle accelerators for many hours and even days, after the explosion.

About the Authors

Prof Markus Boettcher, DSI-NRF SARChI Chair of Astrophysics and Space Physics at North-West University, and the Chair of the South African Gamma-Ray Astronomy Programme. He obtained his Ph.D. in 1997 from the University of Bonn, Germany, followed by research appointments at Rice University and Ohio University in the USA.

Lenté Dreyer is a Ph.D. student in Astrophysics at North-West University. Her research interests lie in the high-energy astrophysics of active galactic nuclei (AGNs) and gamma-ray bursts (GRBs). Her current research focuses on exploiting high-energy polarisation in order to address open questions in our current understanding of astrophysical sources.

Dr. Cornelia Arcaro, born in Germany, has a diploma from Munich University of Applied Sciences and a PhD from the University of Padova. She received the Georg-Simon-Ohm Award by the German Physical Society in 2011 and pursued her career in gamma-ray astronomy as a member of the MAGIC, H.E.S.S. and ASTRI collaborations in Italy and South Africa.



SAAO

COSMOLOGY with the HIRAX Experiment

By Carolyn Crichton, Kavilan Moodley, Anthony Walters, Amanda Weltman

Probing Dark Energy with proudly South African projects

South Africa is leading a cutting-edge, international cosmology and astrophysics experiment - the Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX) - which will tackle two of the most fascinating open problems in cosmology: the nature of dark energy and the driving force behind fast radio bursts (FRBs). HIRAX will use measurements of the latter to answer questions about the former.

Dark energy makes up more than two-thirds of the total energy budget of the Universe and is driving the observed accelerated expansion of the Universe. Yet we have no compelling theoretical model for it. HIRAX will allow us to gain new insights into the properties of dark energy by measuring the evolution of the dark energy equation-of-state (the ratio of its >>

SAAO

pressure to its energy density).

FRBs are mysterious, bright, millisecond flashes observed in the radio portion of the electromagnetic spectrum. They are difficult to detect because they are so brief and most telescopes only have instantaneous coverage of a small region of the sky. HIRAX is designed to detect and catalogue tens of thousands of these bursts, and with outrigger stations in partner African countries, the experiment will localise these bursts with remarkable precision within their host galaxies.

HIRAX will tackle these questions using a radio interferometer array that is currently funded to 256 six-metre dishes, with the goal of expanding the array to 1024 dishes. Interferometer arrays combine signals from many telescopes to provide the resolution of a larger telescope. HIRAX will be a compact interferometer array that is sensitive to larger-scale features in the universe.

HIRAX will study the evolution of dark energy by taking advantage of a unique cosmic ruler provided by nature called baryon acoustic oscillations (BAOs). BAOs were generated in the very early Universe

HIRAX will study the evolution of dark energy by taking advantage of a unique cosmic ruler provided by nature called baryon acoustic oscillations (BAOs).

when small irregularities in the primordial hot and dense soup of particles and light gave rise to sound waves. These waves carried matter as they travelled until a time when matter and light separated, leaving matter distributed in a characteristic pattern.

An excellent tracer of the matter distribution of the universe is *neutral hydrogen* (HI) gas. The HI gas emits a signal at 1420 MHz, which is around the frequencies that cellular networks and television stations use. This signal gets stretched as the universe expands. HIRAX will operate between 400 MHz and 800 MHz allowing it to study dark energy between 7 to 12 billion years ago, a pivotal time in cosmological history.

HIRAX will detect FRBs by taking advantage of the dispersion of these bright flashes to distinguish them from other astronomical sources and radio interference. Much like pulsars in our Milky Way, the components of an FRB are dispersed, with low frequencies arriving at the telescope later than higher frequencies. This delay is governed by the number of free electrons through which the bursts propagate. Since most FRBs appear to emanate from distant galaxies, their dispersion measure provides valuable information on the distribution of ionised gas in our cosmos.

HIRAX is in the process of building the first 256 dishes of its array on the SKA site in the Karoo. The low levels of radio frequency interference in the HIRAX band, together with access to the Southern Sky that is being targeted for a number of large cosmological surveys at other wavelengths, give the experiment a competitive advantage. Once built, the project expects several significant research findings. HIRAX must first detect the brightness of the cosmological HI signal by separating it, using sophisticated data analysis algorithms, from the much larger signal coming from our own galaxy. Direct detection of the HI brightness signal is yet to be achieved due to the extreme precision required. Following such a detection, only then can HIRAX measure the BAO signal and set constraints on the evolution of dark energy.

HIRAX is expected to see up to a dozen FRBs a day, while currently only a few hundred in total have ever been observed. Obtaining the distances to FRBs is essential for them to be useful in cosmology applications, thus identifying their host galaxies is important. Cosmological applications of FRBs include uncovering the properties of dark matter; constraining cosmic curvature; and measuring cosmic acceleration, though the most immediate application may be measuring our local gas density. Since much of the normal matter that is expected to exist in the late-time Universe remains unobserved, these bursts offer an exciting new possibility of explaining the so-called missing baryon problem. Aside from its capacity for new scientific results, HIRAX brings with it technological advances that will be developed locally in South Africa and a huge opportunity for training an entire group of students in all aspects that lead to the development of an experiment of this kind; from the construction of the telescope to computer simulations of expected data, telescope observations, data processing and scientific analysis. It is a locally-led project with immense potential to contribute not only to the knowledge economy of our country but also to the understanding of our Universe on a global scale.

About the Authors

Carolyn Crichton is the project manager from the HIRAX project, led out of the University of KwaZulu-Natal. She is PMI certified and has focused her career on leading highly technical projects in astronomy and aerospace.

Prof Kavilan Moodley is currently full professor at the University of KwaZulu-Natal and director of the Astrophysics Research Centre. He is the principal investigator of the HIRAX telescope project. His research interest is in the area of cosmology, in which he has published 85 research papers with over 6000 citations.

Dr Anthony Walters is a postdoctoral researcher in the High Energy Physics, Cosmology and Astrophysics Theory Group at the University of Cape Town. His research focuses on using FRBs as a cosmological probe, and he is currently working with the HIRAX team to develop the instrument.

Prof Amanda Weltman is the NRF/DHEST South African Research Chair in Physical Cosmology in the Department of Mathematics & Applied Mathematics at the University of Cape Town. Her research interests include problems in high energy physics, cosmology and astrophysics. She is currently working with the HIRAX team on the prospects for the experiment both on the cosmology and Fast Radio Burst sides, expecting the two to connect ultimately.

From Big Data to Big Idea

By Carolina Odman and Bradley Frank

Driving the 4th industrial revolution through astronomical data

Big data. It is a term that one hears over and over again. What is it exactly and why is big data a big deal? Big data is a term applied to massive amounts of information that is generated by automated processes. In science, that means massive amounts of data, of signal and noise, generated by our instruments, our experiments and even our simulations. The ability to “look” at the data surpasses the capacity of conventional desktop or laptop computing. Therefore, we need to develop technology that allows us to explore, visualise and ultimately learn from big data. That is one of the challenges of modern science that most disciplines face, but where astronomy may take the lead.

The concept of a gigantic radio telescope was first discussed in the late 1980s. What would become the Square Kilometre Array (SKA) was based on the ambitious goal of detecting the most distant neutral hydrogen in the Universe. After many workshops, discussions and back-of-the-envelope calculations, a general sketch of the telescope emerged - thousands of receptors distributed across the planet, connected together to form a gigantic synthesised aperture. The sheer ambition and audacity of the concept appealed to astronomers and politicians alike; the SKA was to be a gateway not only to the cosmos, but also to cutting-edge innovation, without which the SKA would not be possible. After all, radio astronomy is truly technology-driven.

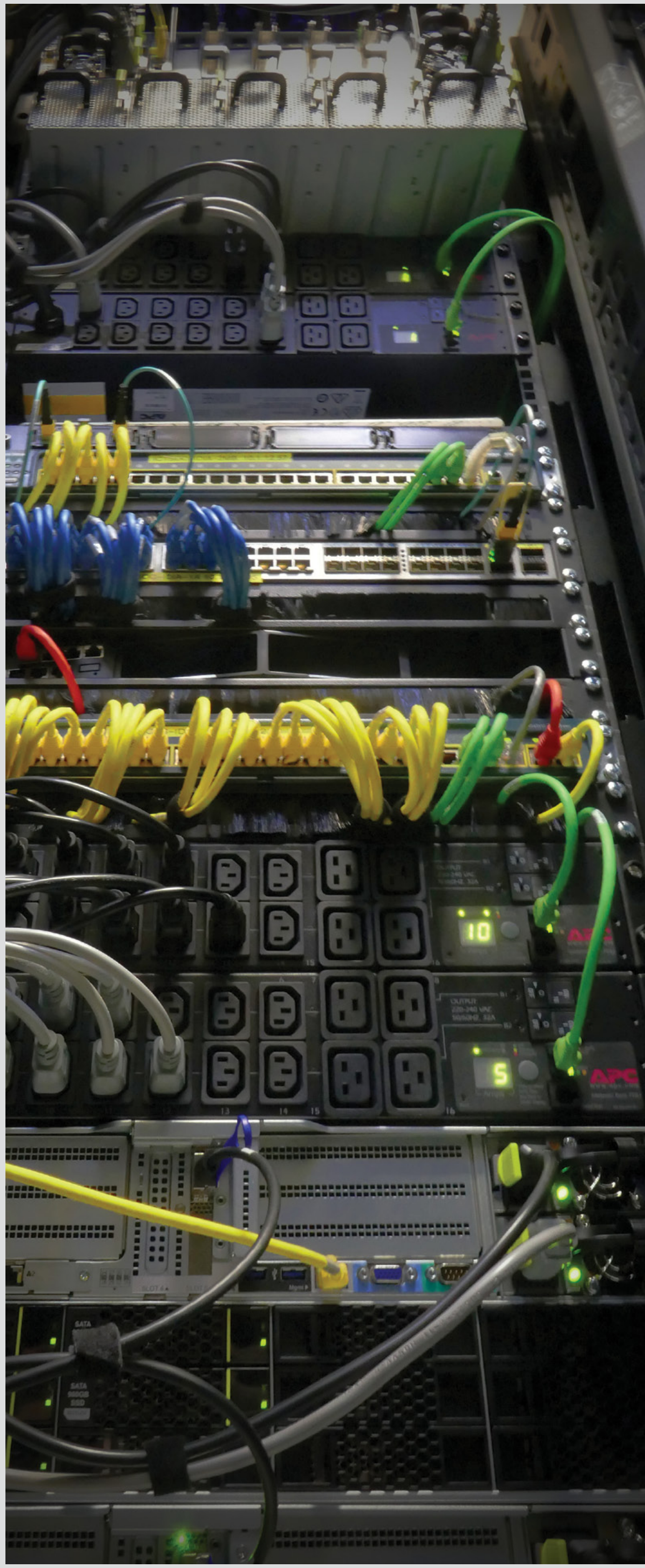
While many of the early SKA documents focused on the order-of-magnitude increase in sensitivity, it quickly became apparent that the telescope, and indeed SKA pathfinders, would generate a deluge of data. Consequently, many of the founders soon realised that, to build and operate a telescope as large as the SKA, scientists would also need large scale computing to process and analyse data on an entirely new scale. This earned the SKA the reputation as an IT project in certain circles.

From its inception, the *MeerKAT* telescope was going to be one of the most advanced astronomical instruments in the world, and scientists from around the world quickly sent in ambitious observing proposals bidding for the telescope’s time. These original projects are the *Large Survey Projects* (LSPs). LSPs would be conducted over many years and comprise thousands of hours of observing time, thus generating petabytes of data, a scale that astronomers had never had to handle. Astronomers were now in the Big Data game.

This enormous challenge was counterbalanced by the opportunity for innovation. LSPs would need access to data centre infrastructure that allowed them to analyse and interrogate the data with enough computing and storage capacity to handle the massive volume of *MeerKAT* data. This is where the Inter-University Institute for Data Intensive Astronomy (IDIA) comes in. IDIA was founded in 2015 by Professor Russ Taylor, SKA Research Chair. The ambition of the institute is to enable researchers at its partner universities (the University of Cape Town, the University of the Western Cape and the University of Pretoria) to process *MeerKAT* data.

The first few years of operation were spent building a research cloud computing facility and exploring large-scale astronomy use-cases. At its official launch in 2018, it had already grown into a bigger project and since January 2019, the IDIA cloud is integrated into *ilifu*, a research cloud facility that >>

SAAO



also serves the bioinformatics community.

To facilitate research is also to develop or adapt suitable scientific software. IDIA has developed a software “pipeline” for *MeerKAT* data, tackling challenges such as radio-frequency interference (*RFI*) detection and elimination, calibration and imaging, all very compute-intensive. IDIA is also part of an international team developing CARTA - scientific visualisation software that enables streaming for visualisation. Indeed, streaming is a new imperative set by the scale of data sets as they cannot be downloaded to any personal computer. A visualisation laboratory working in partnership with the Iziko Planetarium is actively researching and developing immersive data visualisation tools using dome projections or virtual reality to explore science data. These innovations are unique in South Africa and beyond our borders.

With these structures in place, IDIA is able to support research projects led by scientists training many postgraduate students at all partner universities. As of September 2020, six Honours, 20 Masters and nine PhD students have been, or are pursuing, their degrees through IDIA, and 15 postdoctoral researchers are, or have been, supporting their effort. IDIA currently has 13 international collaborations that young researchers benefit from.

IDIA also hosts a Development and Outreach office, with the aim to ensure that all the work done at IDIA benefits society. Carrying out its own research programme as well as coordinating outreach efforts, the office is active in science for development. For example, IDIA is able to leverage its infrastructure to support the Development in Africa with Radio Astronomy (DARA) programmes, a vast big data capacity building initiative across the continent.

DARA big data events can indeed be held anywhere with a network connection, as the training takes place in the cloud. In addition to contributing with access to its research cloud, IDIA sends its members to take part in DARA events as mentors and bring in additional capacity from, e.g. industry.

A decade ago, while some sighed in relief at a Soccer World Cup well planned and executed, we scientists were holding our breath, not knowing if we would be part of the SKA mega-telescope project. Today, we look at the immense progress triggered by the ambition to host the SKA. In a fertile environment with many good initiatives, IDIA has been able to play a leading role in prototyping the SKA pathfinder data processing facility; empowering researchers; training the next generation of radio astronomers; developing data science skills; and positioning South Africa on the world stage of science and technology. This is a great example of how eResearch facilities can play a major role in anticipation of the fourth industrial revolution.

Computing nodes

Number of nodes	Processors per node	RAM per node
110	32 CPUs	256 GB
2	32 CPUs	512 GB
4	32 CPUs 2 Tesla P100 GPUs	256 GB 16 GB

Storage

Size	Type of storage
400 TiB	BeeGFS (scratch storage)
2.9 TiB	CephFS

Table1: The *ilifu* cloud computing and data storage resources as of September 2020

About the Authors

Dr. Carolina Odman is Associate Professor at the University of the Western Cape and Associate Director, Development and Outreach for the Inter-University Institute for Data Intensive Astronomy. She holds an MSc in Physics Engineering from EPFL, Switzerland and a PhD in Astrophysics from Cambridge University, UK.

Dr Bradley Frank is a radio astronomer and Senior Researcher at the South African Radio Astronomy Observatory and the Inter-University Institute for Data Intensive Astronomy

Astrophotography and ASTRO-ART COMPETITION

We encourage photographers, astro-photographers and amateur photographers to submit their shots of the Southern Hemisphere for entry into the competition. The criteria for awarding exhibition space will be the following: deep sky, shallow sky, planets, moon, milky way and constellation.

The Astrophotography Junior allows learners with a cell phone to submit a time lapse short video or photos on the Southern Night Sky.

The Astro-Art competition requires no equipment and learners can submit paintings, sketches and any drawing that they create tagging SAAO or Scifest Africa on our social media platforms.

The competition will run for the whole of October with the first round of winners being announced live by Master KG on Friday, 23 October 2020 at 19h30 on our social media platforms.

By submitting you grant the SAAO permission to post all images on its website and social media.

CONTACT

For any information regarding the event:

PRAN GOVENDER
prang@saao.ac.za

FREDY MASHATE
manager@scifest.org.za

FOLLOW US

NRF National Research Foundation | SAAO South African Astronomical Observatory 200 YEARS

@SAAO
@SAAOnews
@SAAO_astro

EST. 1996 SciFest Africa SOUTH AFRICA'S NATIONAL SCIENCE FESTIVAL

@GHTscifest
@scifestafrica
@scifestafrica