International Centre for Radio Astronomy Research

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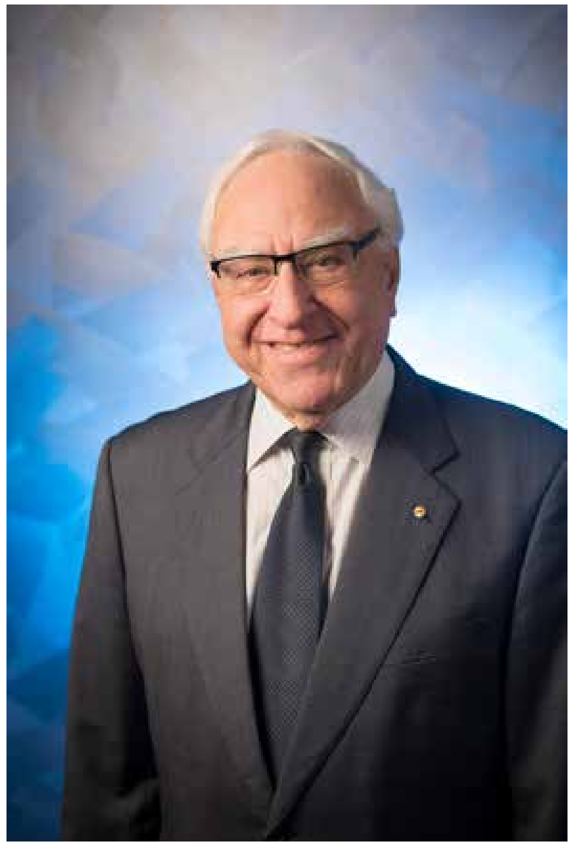
Foreword



The International Centre for Radio Astronomy Research, ICRAR, is a successful partnership of Curtin University, The University of Western Australia and the Western Australian Government.

ICRAR continues to support the Square Kilometre Array (SKA) Project at both national and international levels. It attracts international students, eminent researchers and collaborators, in creating new research initiatives and economic opportunities in science, engineering and data intensive astronomy.

As the current five year plan of ICRAR draws to a close, having successfully completed its research activities and associated applications in support of the SKA project, planning is well advanced to move to ICRAR III from July 2019.

In its new form, ICRAR III will continue to support and add value to the SKA project as it moves to the next phase of development, consolidating ICRAR's position as an international leader in its field in fostering strategic, operational and research initiatives. It will also further strengthen relationships with the SKA project, as well as with other partners related to research and industry.

The benefits delivered by ICRAR will be long lasting and, supported by the collaborative nature of the Centre, ICRAR will reach out to researchers and developers to further enhance its activities and creative opportunities.

I would like to thank the ICRAR partners, members of the Board, the Executive Director, Professor Peter Quinn, and his executive team, the staff of ICRAR and all those who have supported ICRAR in its achievements, as well as in fostering the ongoing constructive relationship with the SKA project and providing a sound basis for future developments.

Hon Dr Ken Michael AC FTSE
Chair of the ICRAR Board

The Milky Way towering over several "dish" antennas belonging to CSIRO's Australian SKA Pathfinder located at the Murchison Radio-astronomy Observatory in Western Australia. Credit: Alex Cherney/ CSIRO.

Chair of the ICRAR Board, Dr Ken Michael.

The MeerKAT radio telescope in South Africa is an SKA precursor consisting of 64 dish antennas each 13.5 metres in diameter. Credit: SKA South Africa.

SKA project update

For the first time, we have a complete picture of what the Square Kilometre Array (SKA) telescope—one of the world's largest science projects—will look like.

Since 2013, researchers around the world have been working together to design all the components of the SKA and its associated infrastructure, from the computing to the hardware and the deployment of the telescope in Australia and South Africa. This effort is broken up into 13 work packages and ICRAR is heavily involved in three: helping to design the low-frequency aperture array, science data processor, and signal and data transport systems for the telescope.

The different work packages are currently undergoing Critical Design Reviews, the final stages of pre-construction. Some areas have already passed their review, and others are expected to do so in the coming months. This is a really important milestone for the project because, once a Critical Design Review has been passed, it means that a particular component of the SKA is ready to be incorporated into the SKA system and eventually be put in a statement of work for tender to begin construction.

The next critical milestone is for those 13 parts to be put together and reviewed holistically in a final system Critical Design Review. This will likely happen towards the end of 2019, giving us a complete picture of the telescope and how we're going to build it. The time between now and then—between the elemental review and the full system review—is known as 'bridging'.

Over the past two years we have seen more countries join the SKA effort, with France and Spain becoming members of the project, and discussions underway with other nations. Another imminent milestone for the telescope is the formation of an intergovernmental organisation (IGO) known as the SKA Observatory. This move from the SKA Organisation as a company based in the UK to an IGO is necessary to take the project into the construction and operations phase.

Top left: The sign as you enter the Murchison Radio-astronomy Observatory, Australia's SKA site.

Top right: A prototype SKA-low antenna on site in the Murchison.

Bottom: Adjusting equipment at the SKA prototype array at Australia's SKA site.

It's a powerful construct that facilitates the movement of money, goods and people between countries, and will carry the project into the future for the next 50 years or more. As such, governments ratifying the IGO agreements and creating the SKA Observatory, or the SKAO, will be an important event in the history of the telescope.

Even more exciting is that the telescope is on track for construction to start at the end of 2020. This is the time ICRAR has been training for. There'll be more opportunities for contracts with the telescope, and the Centre will build on its pre-construction experience to take on some of the services required during this phase.

An aerial view of the Aperture Array Verification System test platform located at the Murchison Radio-astronomy Observatory.

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Looking back and looking forward

From its inception as a handful of researchers in 2009, ICRAR has grown to become one of the top five astronomy research institutes in the world.

As ICRAR approaches its 10th birthday, the organisation is coming of age. The Centre is home to a significant research community, with 117 staff and 82 postgraduate students across two universities. Ten years ago there were almost no astronomers in Western Australia. Now, largely because of ICRAR, nearly one third of the Australian astronomy community lives on the West Coast.

A 2017 Deloitte report found that for every dollar the State Government invested in ICRAR, four dollars and fifty cents was created in income to the state. For every job that the State Government gave ICRAR money for, the Centre created three jobs.

Also in 2017, a 'Visiting Committee' of leaders from astronomy organisations around the world completed a 360 degree review of ICRAR. Their report was extremely positive about ICRAR as an international organisation, calling the Centre a leader in radio astronomy research, and astronomy research in general, as well as a critical component of the SKA project. The Centre is also among the top five radio astronomy research centres in the world, based on publications and citations.

Top left: Professor Andreas Wicenec, head of ICRAR's Data Intensive Astronomy team.

Middle-top: ICRAR's Executive Director, Professor Peter Quinn.

Top-right: John Curtin Distinguished Professor Steven Tingay, Deputy Executive Director of ICRAR.

HRH Prince Andrew discussing the SKA with ICRAR-Curtin researcher Dr Gemma Anderson and ICRAR-UWA PhD candidate Robin Cook.

WA Minister for Innovation and ICT, the Hon Dave Kelly and Federal Minister for Industry, Innovation and Science, Senator Arthur Sinodinos AO visiting the Murchison Radio-astronomy Observatory. Credit: SKA Australia.

Bottom-left: ICRAR Chair, Dr Ken Michael AC.

Bottom-middle: Dr Renu Sharma, ICRAR's Associate Director and Chief Operating Officer.

Bottom-right: The Hon Dave Kelly and Senator Arthur Sinodinos AO visiting the MRO's solar array. Credit: SKA Australia.

A big milestone for ICRAR in 2018 was the extension of funding from the State Government and the two joint venture partners—Curtin University and The University of Western Australia—backing the Centre for a further five years. The State Government agreed to support ICRAR with $25 million and the universities $17.5 million each, for a total of $60 million. This funding will support the third stage of the Centre—ICRAR III—which will run from July 2019 to June 2024.

Looking into the future, ICRAR will continue to focus strongly on its core strengths; astronomy, engineering and data science. But the Centre will turn up the knob on industry engagement, focusing on translation and impact, and aiming to attract funding from a variety of sources. ICRAR will employ business development staff to help the Centre develop and nurture relationships with industry, and generate beneficial outcomes for commercial partners.

ICRAR wants to allow industry to capitalise on the Centre's expertise in engineering, data science and astronomy, and make use of the innovative ideas ICRAR has developed on the path to building the SKA. The Centre wants to find opportunities where radio astronomy skills might be translatable to a broad range of industries that are important for WA's and Australia's future.

With the SKA heading into the construction phase, there'll be more opportunities for contracts with the telescope, and ICRAR will build on its pre-construction work and engage with the SKA to take on some of the services required during this phase.

The Centre will also continue to encourage high school students to study STEM, and inform and motivate the general public about the SKA project. The telescope has the potential to translate into multiple areas and bring benefits to industry, as well as inspiring young people to consider careers in technology.

Both nodes of ICRAR are still growing and expanding their footprint at the two universities, with long-term research projects beginning to pay dividends, and construction of the SKA imminent. It's an exciting five years ahead.

Governance and Management

Governing Board as at 31 Dec 2018 (Appointed until 30 June 2019)

Dr Ken Michael	Chair (2016)
Mr Graham McHarrie	Independent member (2009)
Professor Chris Moran	Nominated member Curtin University (2016)
Professor Robyn Owens	Nominated member The University of Western Australia (2012)
Dr Tom Hatton	Independent member (2014)
Ms Fiona Roche	Nominated member Department of Jobs, Tourism, Science and Innovation (2015)
Ms Erica Smyth	Independent member (2016)
Dr David Williams	Nominated member CSIRO (2015)
Professor Virginia Kilborn	Independent member (2018)

Past Board Members 2017-18

Professor Ron Ekers	Independent member (2012)

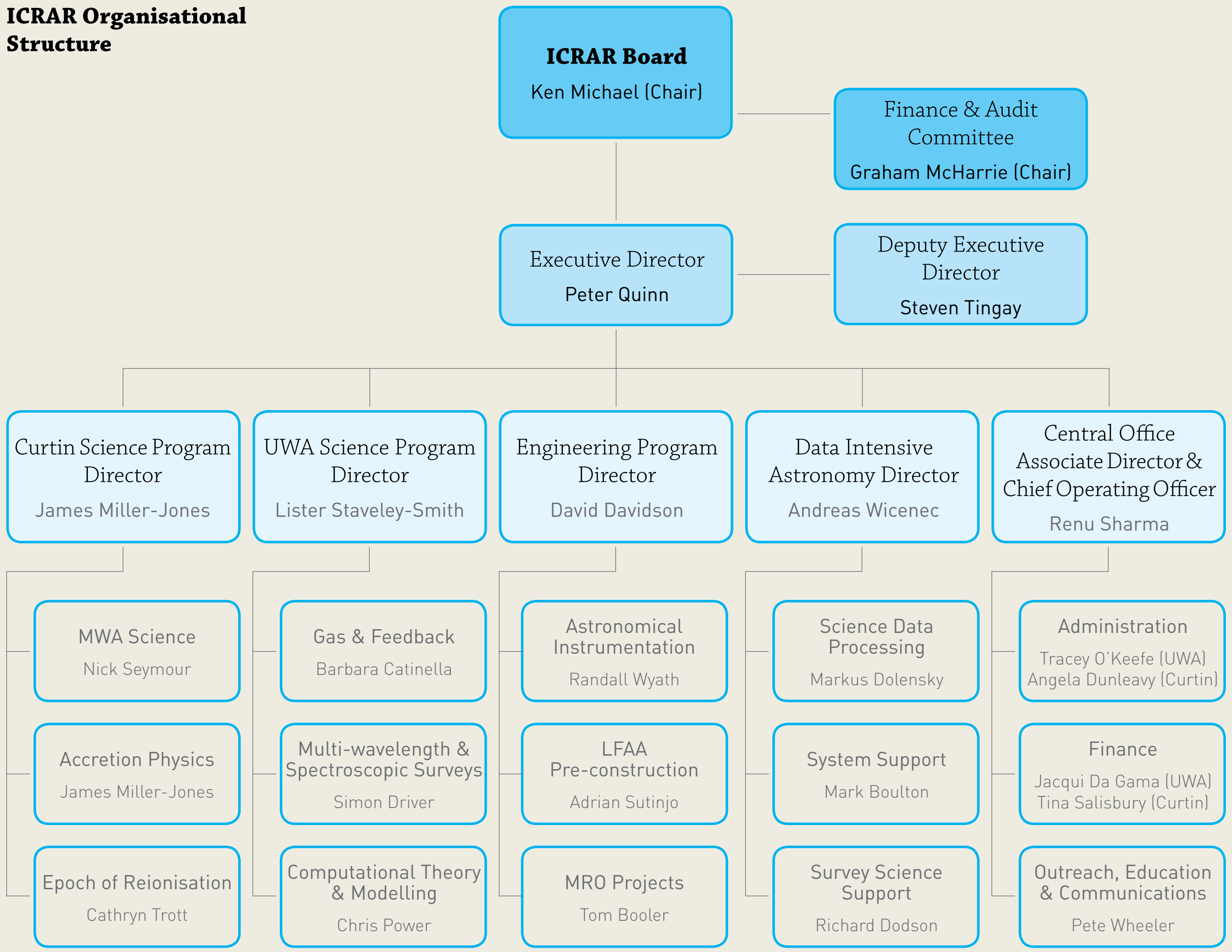
Finance and Audit Committee as at 31 Dec 2018 (Appointed until 30 June 2019)

Mr Graham McHarrie	Chair (2010)
Mr Mark Woffenden	Member (2010)
Dr Tom Hatton	Member (2014)
Ms Nicole O'Connor	Nominated member Curtin University (2018)
Dr Claire Patterson	Nominated member Department of Jobs, Tourism, Science and Innovation (2018)

Executive Team as at 31 Dec 2018

Professor Peter Quinn	Executive Director and Chief Executive Officer
Professor Steven Tingay	Deputy Executive Director
Professor David Davidson	Director of Engineering
Dr Renu Sharma	Associate Director and Chief Operating Officer
Professor Lister Staveley-Smith	Director of Science at ICRAR-UWA
A/Professor James Miller-Jones	Director of Science at ICRAR-Curtin
Professor Andreas Wicenec	Director of Data Intensive Astronomy at ICRAR-UWA

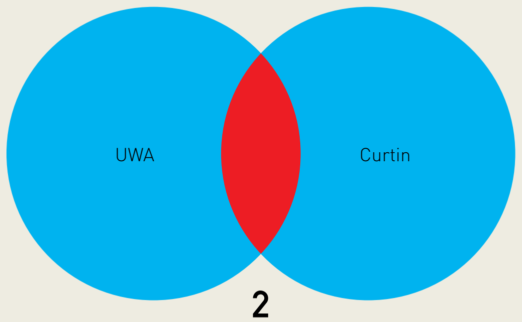
ICRAR Organisational Structure



ICRAR at a glance

The following pages will give you a quick snapshot of the key totals for ICRAR since our inception.

Since ICRAR began in September 2009…



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Research nodes

1,521 refereed papers

34,860 citations for ICRAR-authored papers

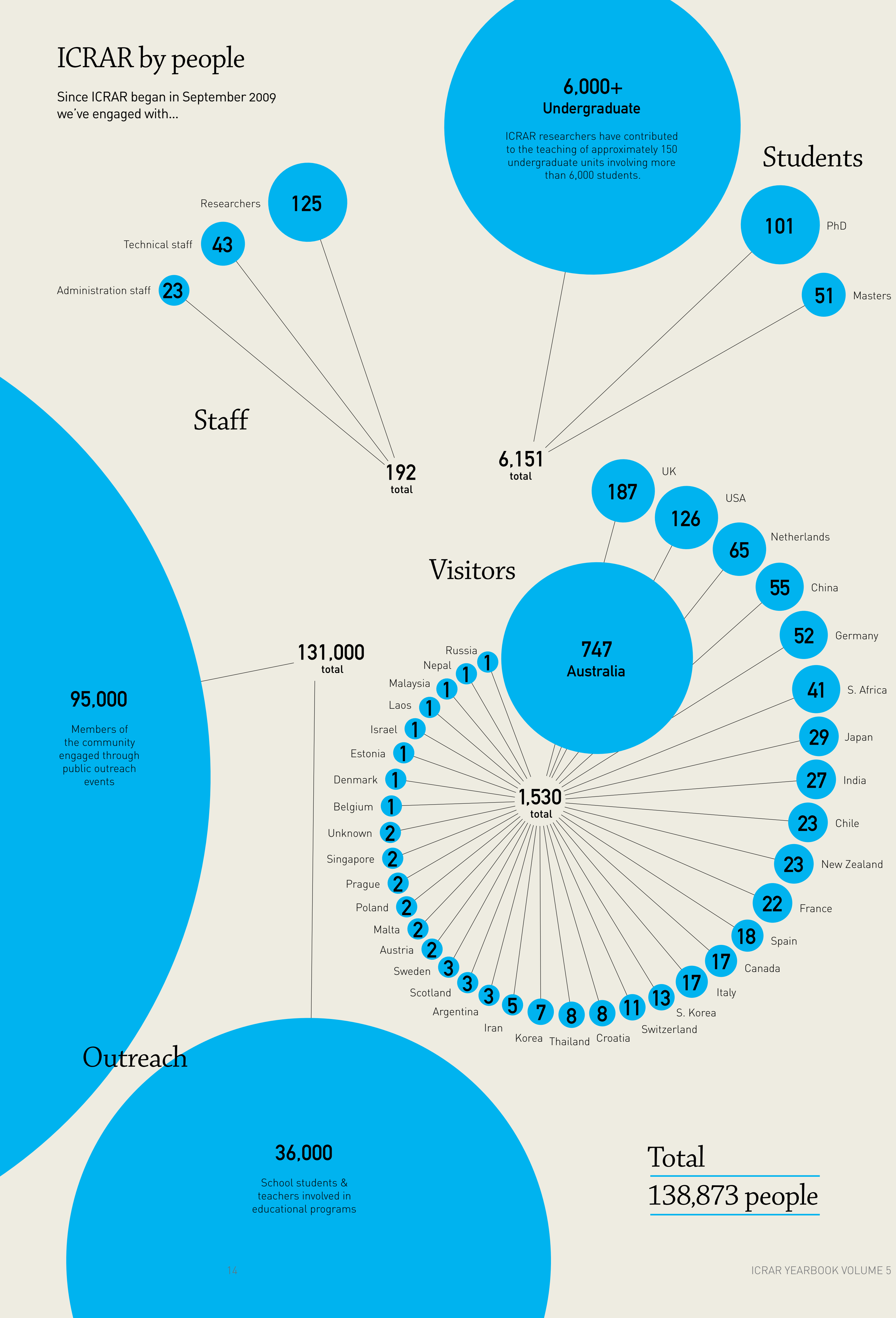
28,944 hours of telescope time awarded

39.4 million hours of supercomputer time awarded

$77.8 million won in external grants

ICRAR by people

Since ICRAR began in September 2009 we've engaged with...



Total

138,873 people

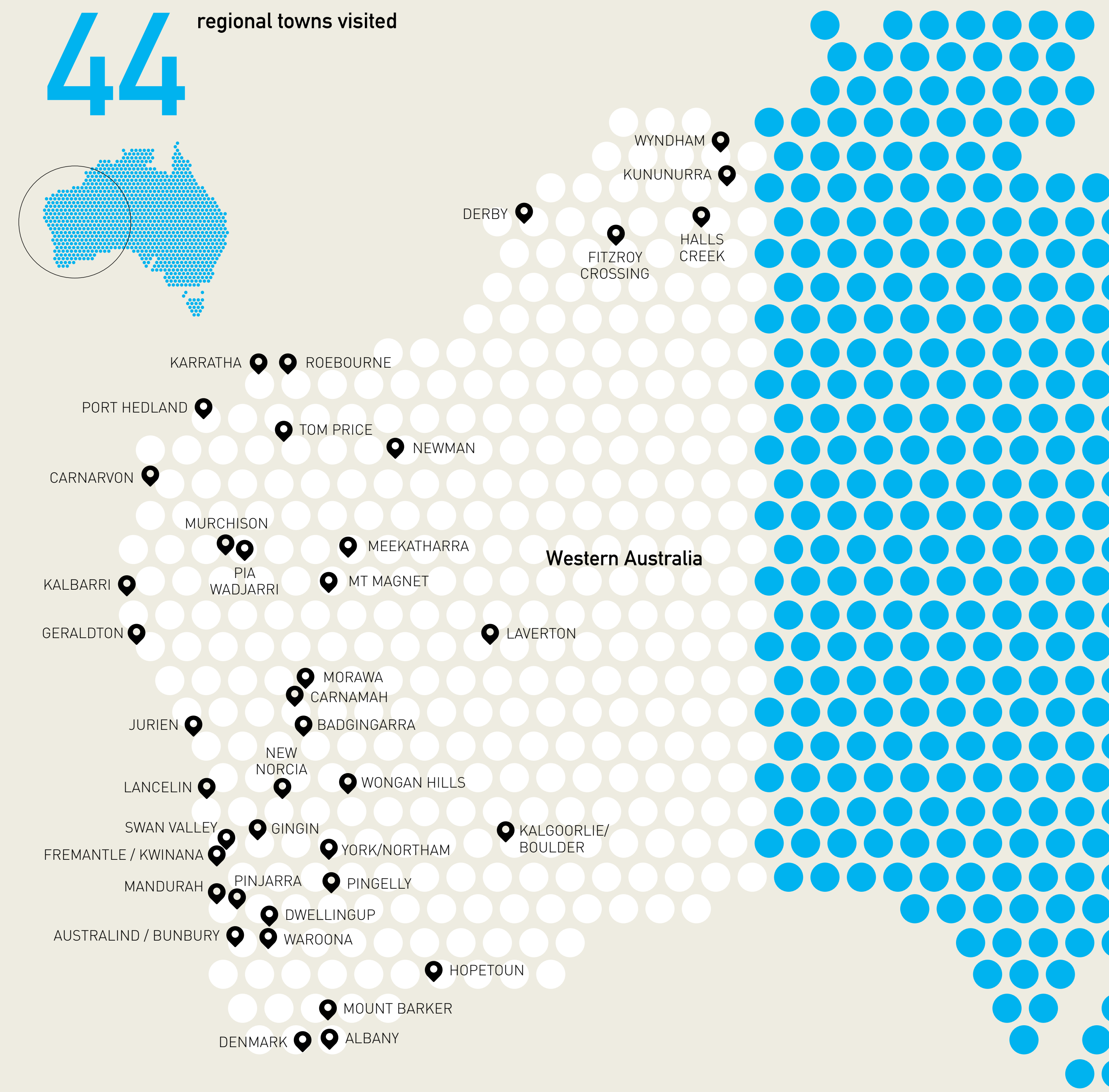
Outreach, Education and Communications

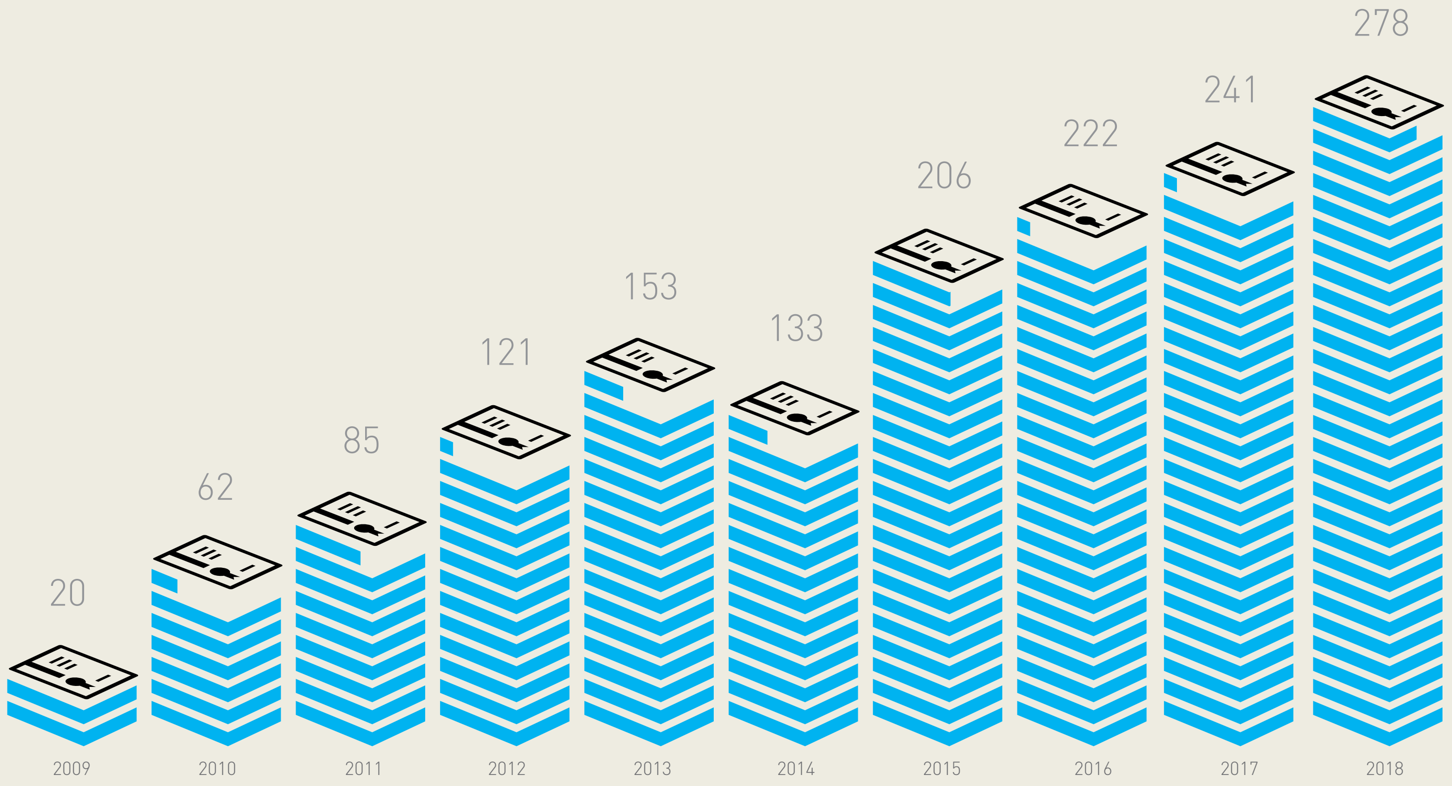
122 media releases distributed

10,000+ media articles world-wide about ICRAR research

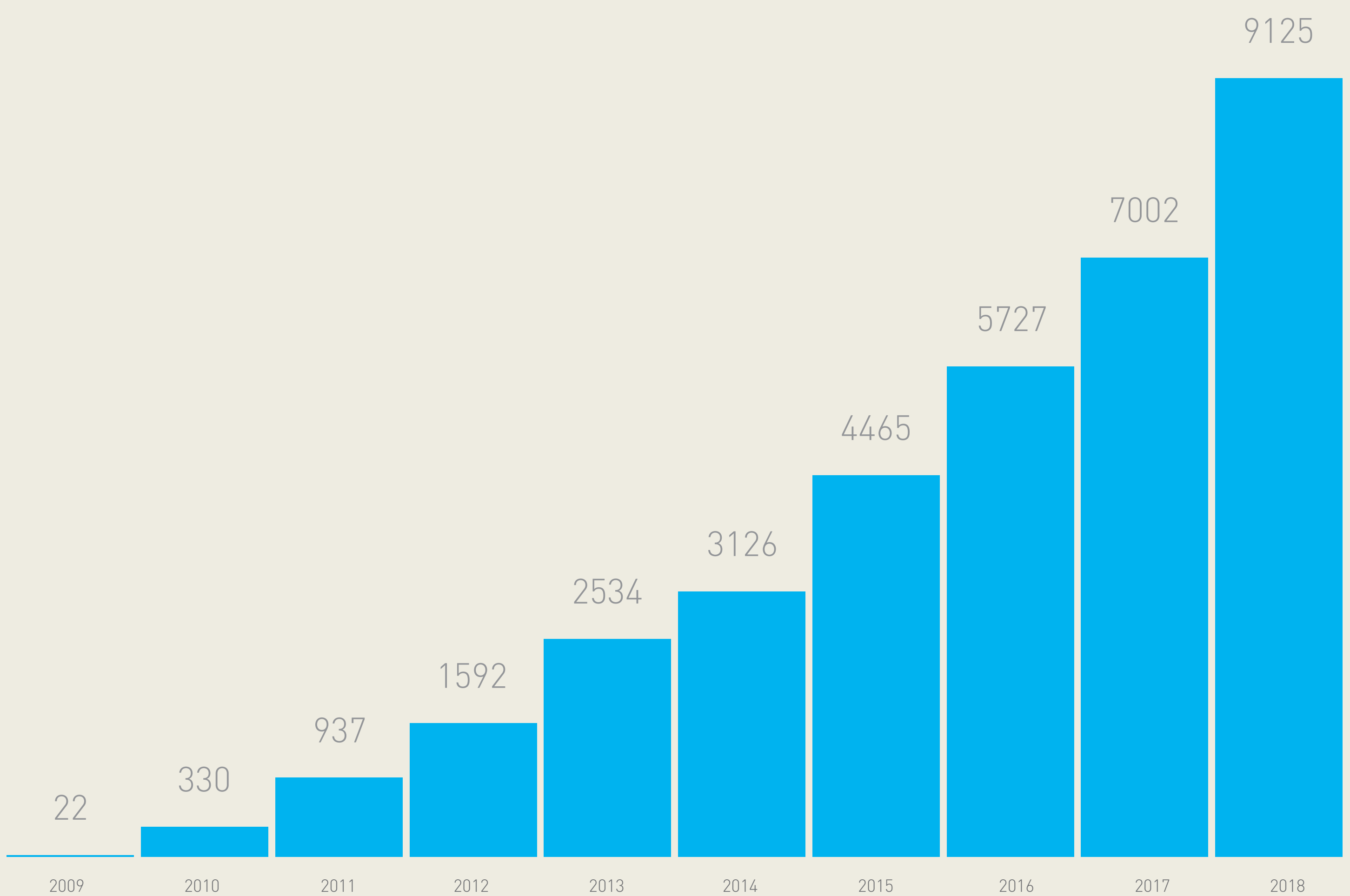
$650,000 won

44 regional towns visited



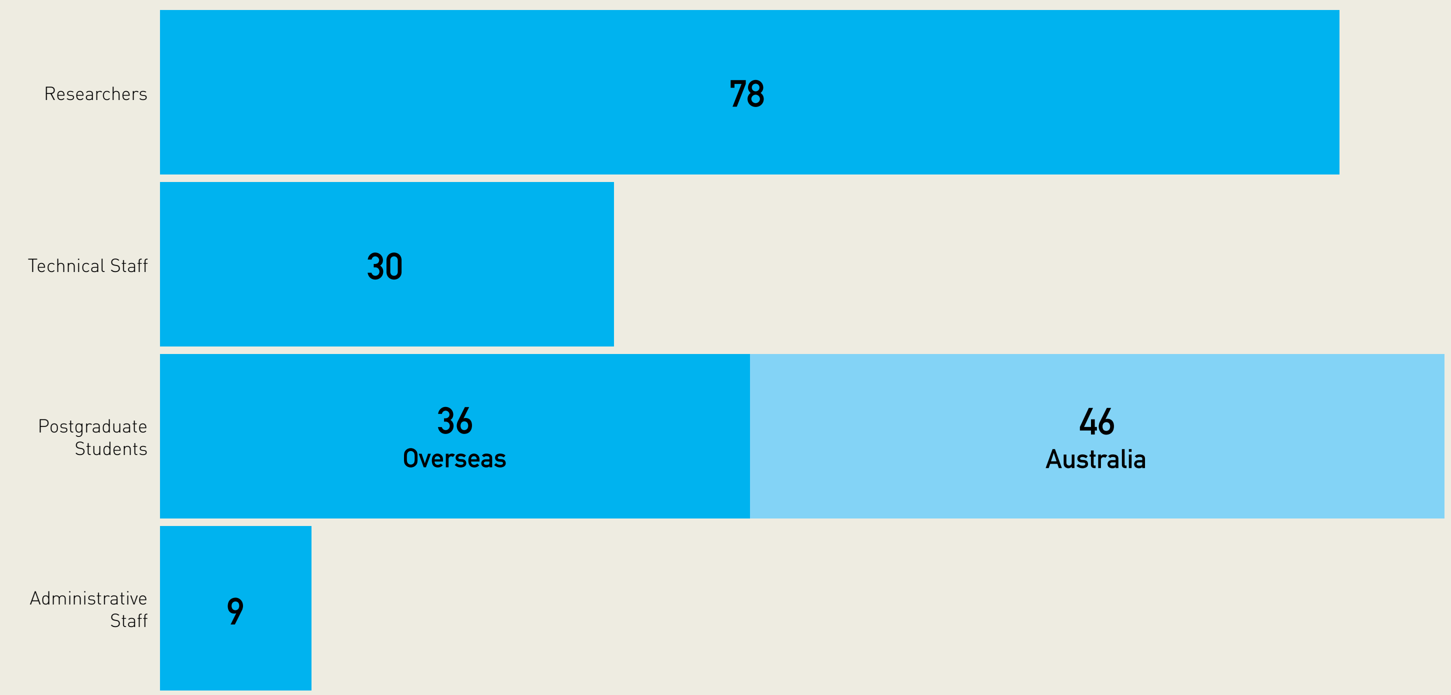


Refereed Papers 2009 to 2018



Cumulative citations for ICRAR authored publications
Annual citations (ADS refereed definition)

Our people



Current ICRAR Profile —2018

ICRAR Visiting Fellowship for Senior Women in Astronomy

ICRAR is committed to supporting women in astronomical sciences and technology. This fellowship provides an opportunity for senior women astronomers, engineers and data scientists working in the field of astronomy to work with and mentor our researchers and graduate students.

Associate Professor Anna Frebel (2017-18)

MIT, Cambridge, MA, USA

Dr Francesca Primas (2016-2017)

European Southern Observatory, Germany

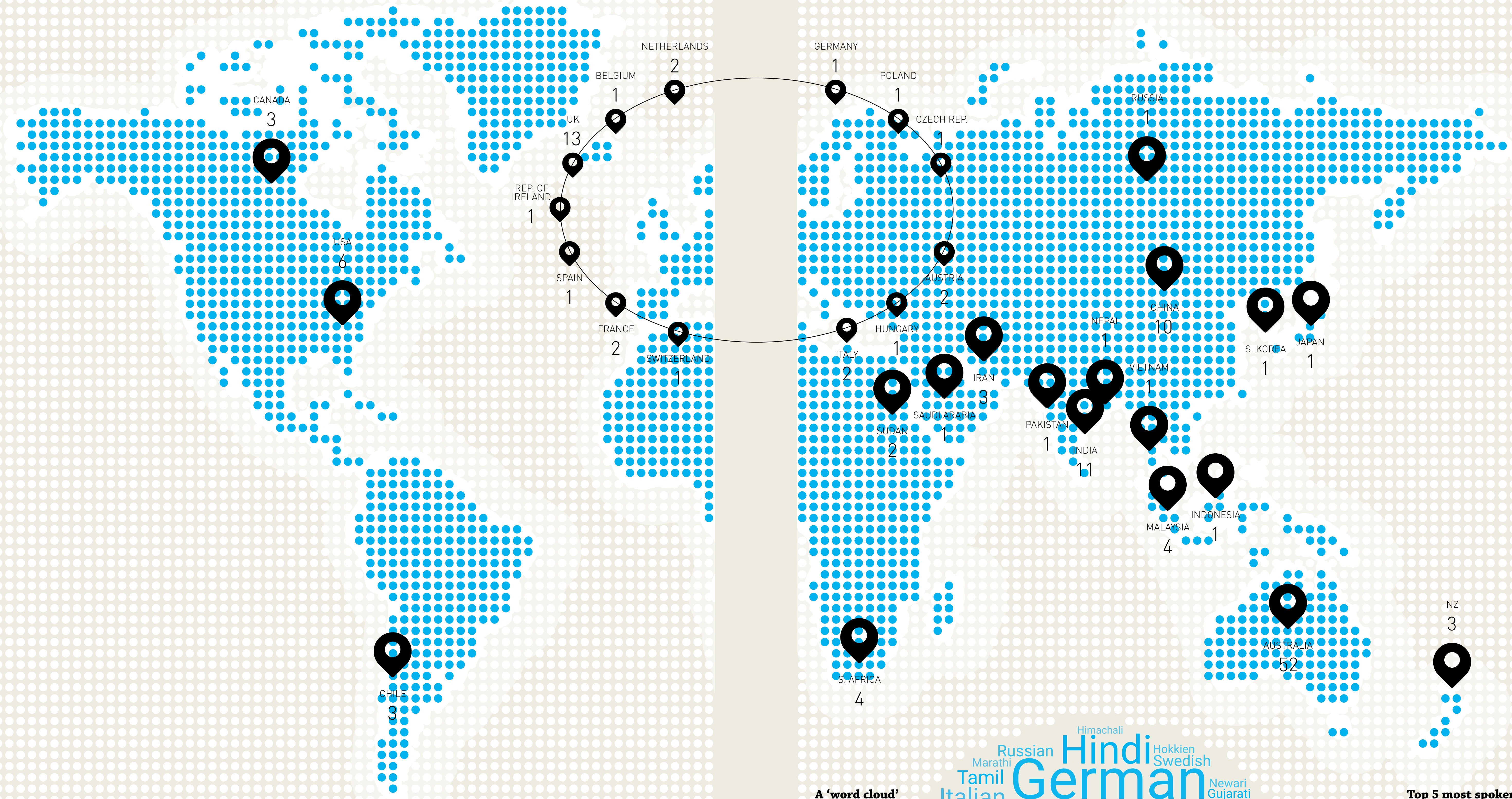
Associate Professor Vernesa Smolcic (2015-2016)

University of Zagreb, Croatia

Dr Andreea Font (2014-2015)

Liverpool John Moores University, United Kingdom

An International Centre:
ICRAR staff by country of birth



Location by Jivan
from the Noun Project

A 'word cloud' showing the cultural and language distribution at ICRAR

Top 5 most spoken languages at ICRAR

1	English
2	French
3	German
4	Hindi
5	Chinese/Spanish

ICRAR's supportive research environment

ICRAR organises a range of activities at both Curtin and UWA to bring staff and students together and encourage collaboration across disciplines.

Athena SWAN Bronze Award (SAGE)
Curtin University

Research group meetings

Research groups conduct their own team meetings to discuss research projects and bring the team together for updates.

Professional Development

Researchers and students are offered a wide range of professional development opportunities including training in communication skills for those looking to develop media skills, presentation skills and use of social media to communicate their research.

Induction

With the majority of people recruited internationally, staff and students are assisted with relocation support, temporary accommodation and a detailed induction.

Weekly seminars

Held on Tuesdays and Thursdays at child-friendly times at both ICRAR-Curtin and ICRAR-UWA. Talks are given by visitors, local staff or experts from other institutions, and are open to the public.

Journal club

Weekly journal clubs are held at ICRAR-Curtin and at ICRAR-UWA. These provide an opportunity for researchers to come together and discuss journal articles.

All Hands meetings

All Hands meetings update staff and students on important matters, and enable them to meet members of ICRAR's Board.

./Error1'

StdErr

A weekly forum at ICRAR-Curtin for staff and students to get together to discuss tips, tricks, and issues in the computing space. STDERR is language agnostic and driven by the needs of the group which change throughout the year.

Write club

Every Monday at ICRAR-UWA and every Wednesday at ICRAR-Curtin, this provides a few hours of dedicated time to get together and write.

Astro morning tea

Every Wednesday at ICRAR-UWA. This weekly one-hour hit of interesting scientific information is also used to highlight funding opportunities and student work.

SAGE member
UWA

de Laeter Colloquium

This monthly colloquium series aims to enhance collaboration between the two ICRAR nodes, CSIRO and high-profile centres of astronomical research around the world.

Silver Pleiades Award - Recognising Commitment to Advancing Women in Astronomy
ICRAR-UWA

Wellbeing workshops

Wellbeing and resilience events are held for both staff and students.

Friday morning tea

Held every Friday at ICRAR-UWA, this social and informative morning tea often showcases international food. As part of our commitment to cultural inclusion, the ICRAR-Curtin development committee also runs occasional morning teas to mark specific cultural events.

ICRAR-Con

A three-day retreat for all staff and students held in the first week of September, including a mix of talks and social activities. Previous events have been held at Seashells Resort Mandurah and Rottnest Island.

Plot of the week

Every Friday at ICRAR-UWA students get together to discuss research results and ask questions.

Student presentation day

All ICRAR staff and students are invited to come together once a year for talks from PhD and Masters students. A separate presentation day is held for summer interns.

Visitors

ICRAR welcomes more than 200 national and international collaborators every year.

Staff committees

A development committee, based at ICRAR-Curtin, and a diversity, equality and inclusion committee, based at ICRAR-UWA, meet monthly to improve staff wellbeing. The committees' remits include race, gender, inclusivity, unconscious bias and development.

Radio galaxy morning tea

Radio galaxy morning tea is held at 10am each Thursday, rotating between ICRAR-Curtin, ICRAR-UWA and CSIRO-Perth. The aim of this morning tea is to facilitate an informal discussion on the latest research in radio astronomy and/or galaxy evolution science. This cross-institutional discussion group helps foster further research collaboration between the three institutes.

Visiting fellowship for senior women in astronomy

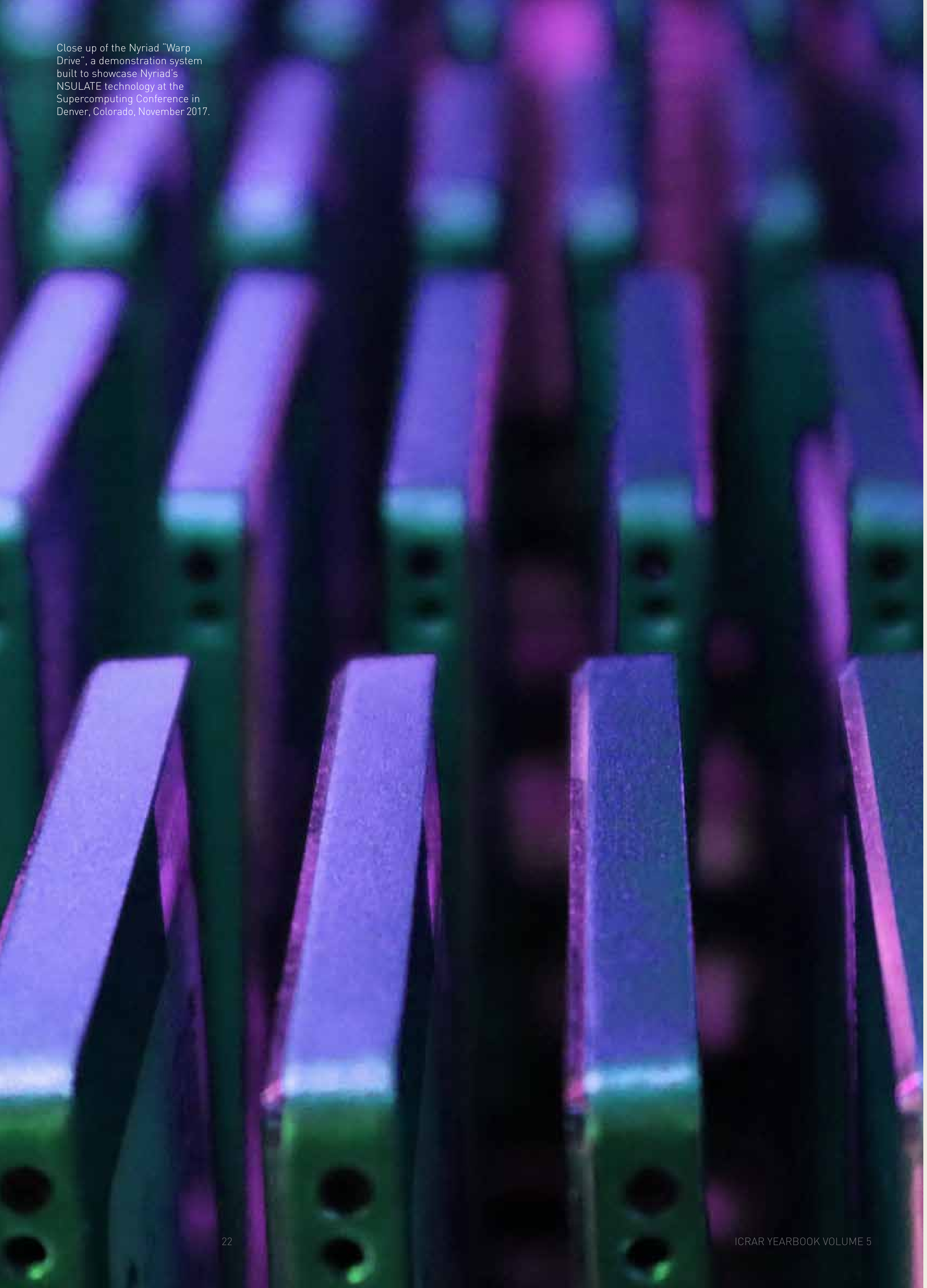
A three-month fellowship that sees a senior female researcher share her journey with other women in astronomy. The recipient imparts stories and specific strategies to young students and staff, to help more women reach higher levels in academia.

Shared spaces

Both ICRAR-Curtin and ICRAR-UWA have tearoom facilities and outdoor spaces.

Bronze Pleiades Award - Recognising Commitment to Advancing Women in Astronomy
ICRAR-Curtin

Credits: Teaching by B Farias, Meet by Sergey Demushkin, Magazine Reading by Andrey Vasiliev, Pencils by Creative Stall, Tea by Kaylen, Galaxy by Vladimir Belochkin, Comet by Ilaria Bernareggi, Code by Dmitrij, Public Speaker by Darrin Loeliger, Class by David, Cooperation by Matias Porta Lezcano, Meeting by Claire Jones, Coworking by Gregor Cresnar, Presentation by Gregor Cresnar, Scatter Plot by Allen, Cinema by Abdo, Women Population by Deepak, Heart by Piger, People by Magicon, Research by Gregor Cresnar, Apple by ProSymbols, Calendar by Lyhn, Mental Health by Gemma Evans, Globe by Berkah Icon, Award by Taolao. All from the Noun Project.



Close up of the Nyriad "Warp Drive", a demonstration system built to showcase Nyriad's NSULATE technology at the Supercomputing Conference in Denver, Colorado, November 2017.

Partnerships and collaborations

Nyriad
Industry partner

Kiwi start-up Nyriad's flagship product was developed in partnership with ICRAR for the Murchison Widefield Array (MWA) telescope. The product—known as NSULATE—represents a new way of storing information that could revolutionise how the world manages big data. Nyriad is one of the first commercial spin-offs from the international SKA effort.

For more, see page 55.

CSIRO
Academic partner

Researchers from ICRAR and CSIRO collaborate closely on a wide range of projects. Many are focused around the ASKAP and MWA telescopes, which sit side-by-side in Western Australia's remote Murchison region. In a study published in 2018, ICRAR and CSIRO arranged for the two telescopes to point at the same area of sky at the same time, resulting in new discoveries about mysterious flashes of energy known as fast radio bursts.

For more, see page 27.

Shanghai University and National Astronomical Observatories of the Chinese Academy of Sciences
Academic partner

ICRAR has developed strong collaborations with colleagues in China, covering astronomy and technology. The partnerships with Shanghai University and the National Astronomical Observatories in Beijing and have provided academic, scientific and technical access to some of the planet's most cutting-edge facilities. These include the world's third fastest supercomputer—Tianhe-2—and the FAST radio telescope.

Amazon Web Services, Microsoft Azure, EngineRoom.io and Datacom
Industry partners

ICRAR have received a significant amount of cloud computing credit from Amazon Web Services and Microsoft Azure, who are interested in the Data Intensive Astronomy team conducting large-scale projects in the cloud. The Data Intensive Astronomy team also works closely with specialised software service providers EngineRoom.io and IT service provider Datacom on a range of innovative projects.

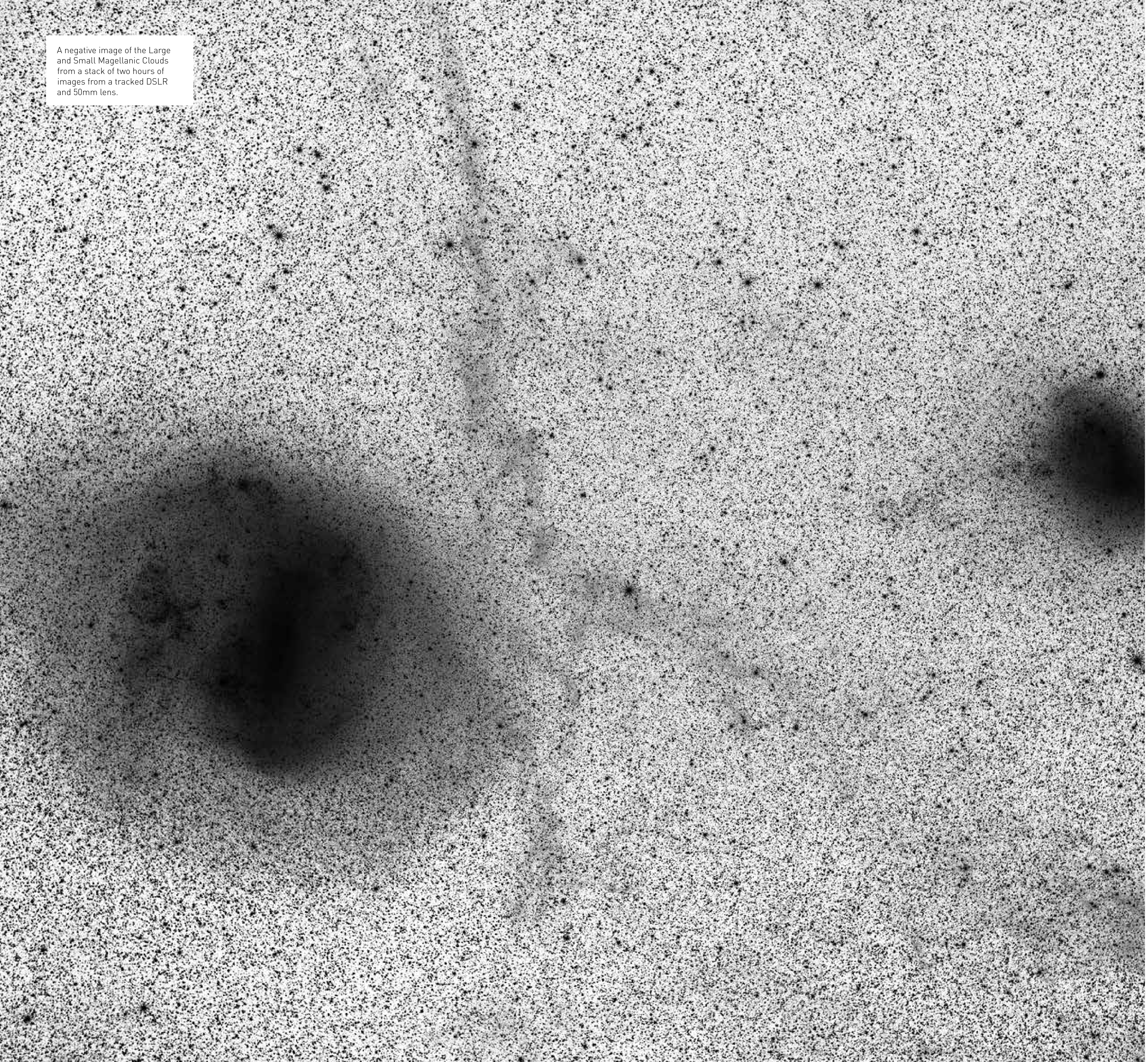
Silentium
Industry partner

In 2018, ICRAR teamed up with Adelaide company Silentium Defence to develop a passive radar for the surveillance of objects in space. The partnership will see the super-sensitive MWA radio telescope used to record radio waves bouncing off objects in Earth's orbit.

For more, see page 48.

2020 Asia-Pacific Regional International Astronomical Union Meeting
Academic partner

ICRAR and CSIRO will co-host the 14th Asia-Pacific Regional Meeting of the International Astronomical Union in Perth in 2020. The two organisations delivered a strong bid to bring the event to Western Australia at the 2017 meeting in Taiwan.



A negative image of the Large and Small Magellanic Clouds from a stack of two hours of images from a tracked DSLR and 50mm lens.

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Overview

Long-term projects are beginning to pay dividends for ICRAR astronomers.

The last year saw huge leaps in our understanding of fast radio bursts, mysterious flashes of energy from deep space. ICRAR astronomers were part of a team which used the Australian SKA Pathfinder (ASKAP) telescope to almost double the known number of fast radio bursts, and used the Murchison Widefield Array (MWA) telescope to find the bursts cannot be detected at low frequencies. The Centre was also involved in a study of the only fast radio burst known to repeat.

In July 2017, the ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions, or ASTRO 3D, was launched. This collaborative research organisation involves six Australian universities, including Curtin University and The University of Western Australia, and ICRAR is heavily involved in several ASTRO 3D research projects.

The Murchison Radio-astronomy Observatory—home to CSIRO's Australian SKA Pathfinder (ASKAP) and the Murchison Widefield Array (MWA) radio telescopes, and the future location of 130,000 low frequency antennas for SKA-low. Credit: CSIRO/ICRAR-Curtin.

An expansion of the MWA telescope has allowed astronomers to see the Universe in more detail at low frequencies. This expansion, known as MWA Phase 2, makes use of long baselines to probe deeper into the Universe. It has also allowed researchers to study how the intergalactic medium makes objects appear to twinkle, just as the Earth's atmosphere makes stars twinkle.

ICRAR has seen a strengthening of the team searching for faint signals from the Epoch of Reionisation, a time early in the history of the Universe when the first stars appeared. As part of this, ICRAR researchers observed the Moon with a radio telescope to try and calculate the average brightness of the sky.

ICRAR astronomers have also seen success in early science from the WALLABY and DINGO surveys on the ASKAP telescope. The full WALLABY survey—by far the largest radio survey for gas ever conducted—kicks off in 2019, and scientists are excited by what it will find.

ICRAR continues to be at the forefront of many neutral hydrogen surveys of the local Universe, and trying to understand the astrophysics of galaxies by combining data across multiple wavelengths. The Centre also has a very strong team researching white dwarfs, neutron stars, black holes and the jets these objects produce.

ICRAR is home to one of Australia's leading simulations groups, using computer modelling to test the laws of physics. In the past two years, ICRAR's astronomers discovered more about two of our nearest neighbours, the Large and Small Magellanic Clouds, and joined forces with the Data Intensive Astronomy team to use artificial intelligence to automatically classify galaxies.

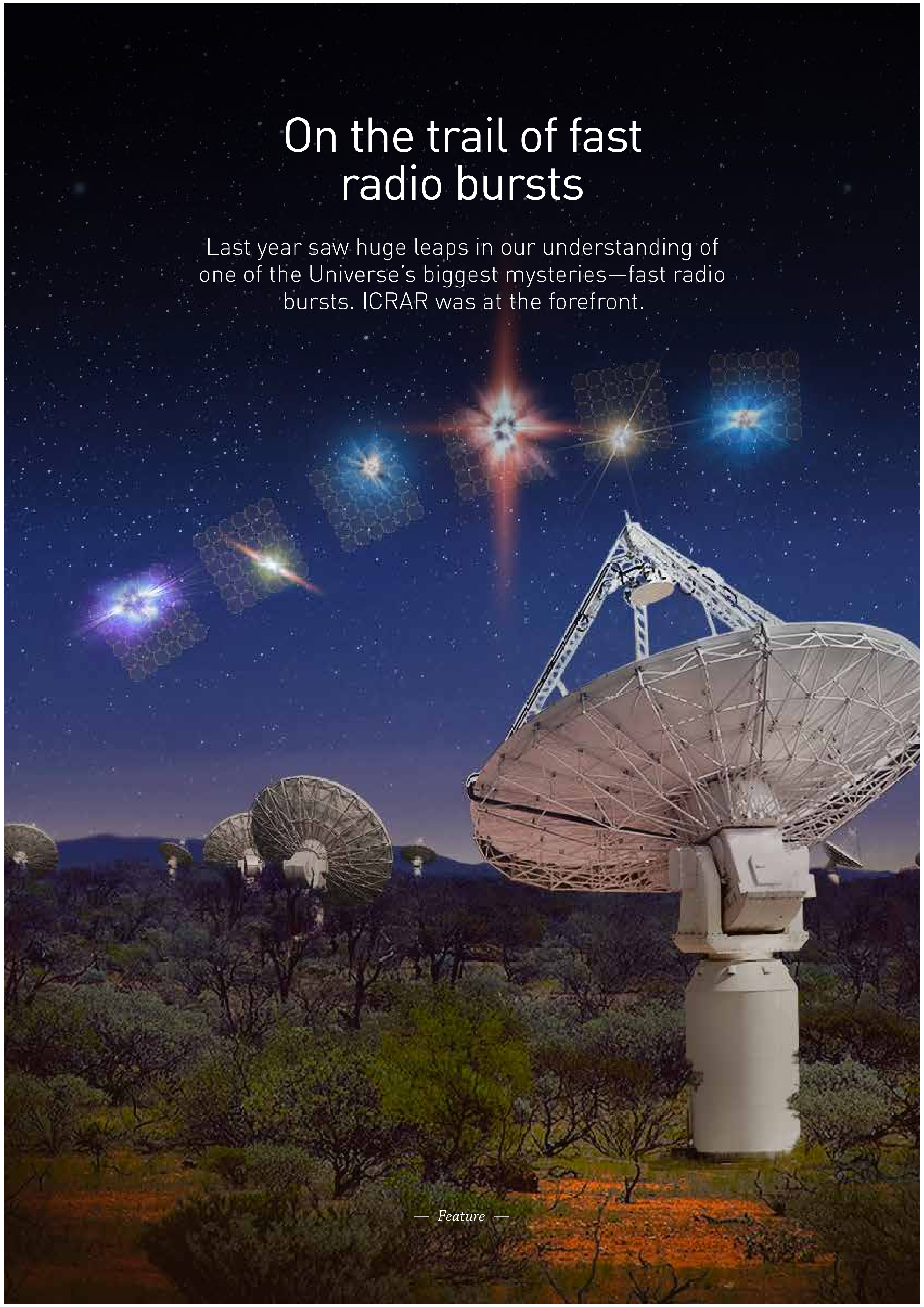
ICRAR astronomers also discovered more about a special type of galaxies called 'ring galaxies', high-velocity clouds, and star formation over the history of the Universe. They studied cosmology using the 2MTF survey—which combines observations from the Green Bank, Arecibo and Parkes telescopes—and galaxies using the xGASS survey on Arecibo.

ICRAR researchers and students have won several awards (see page 77) including WA Young Tall Poppy Awards in 2017 and 2018 (Dr Natasha Hurley-Walker and Dr Luke Davies, respectively), the ExxonMobil Student Scientist of the Year Award in both 2017 and 2018 (David Gozzard and Ryan Urqhart, respectively), and the inaugural Astronomical Society of Australia's Anne Green Prize, awarded to Barbara Catinella in 2018.

ICRAR and CSIRO co-hosted the largest radio astronomy school ever in Australia, with 65 postgraduate research students and 20 lecturers from around Australia and the world. The week-long school was held in Geraldton, and included a visit to the Murchison Radio-astronomy Observatory—home to the MWA and ASKAP telescopes.

On the trail of fast radio bursts

Last year saw huge leaps in our understanding of one of the Universe's biggest mysteries—fast radio bursts. ICRAR was at the forefront.



— Feature —

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An artist's impression of CSIRO's ASKAP radio telescope detecting a fast radio burst (FRB). Scientists don't know what causes FRBs but it must involve incredible energy—equivalent to the amount released by the Sun in 80 years. Credit: OzGrav, Swinburne University of Technology

Antennas of CSIRO's Australian SKA Pathfinder with the Milky Way overhead. Credit: Alex Cherney/CSIRO

FOLLOWING PAGE

An artist's impression showing fast radio bursts in the sky above CSIRO's ASKAP radio telescope.

FRB signal samples. For each burst, the top panels show what the FRB signal looks like when averaged over all frequencies. The bottom panels show how the brightness of the burst changes with frequency. The bursts are vertical because they have been corrected for dispersion. Credit: Ryan Shannon and the CRAFT collaboration.

Ever since their discovery a decade ago, astronomers have been perplexed by exceptionally bright flashes of energy coming from deep space. These bursts of radio waves come from all over the sky and last for just milliseconds. Scientists don't know what causes them but it must involve incredible energy—equivalent to the amount released by the Sun in 80 years.

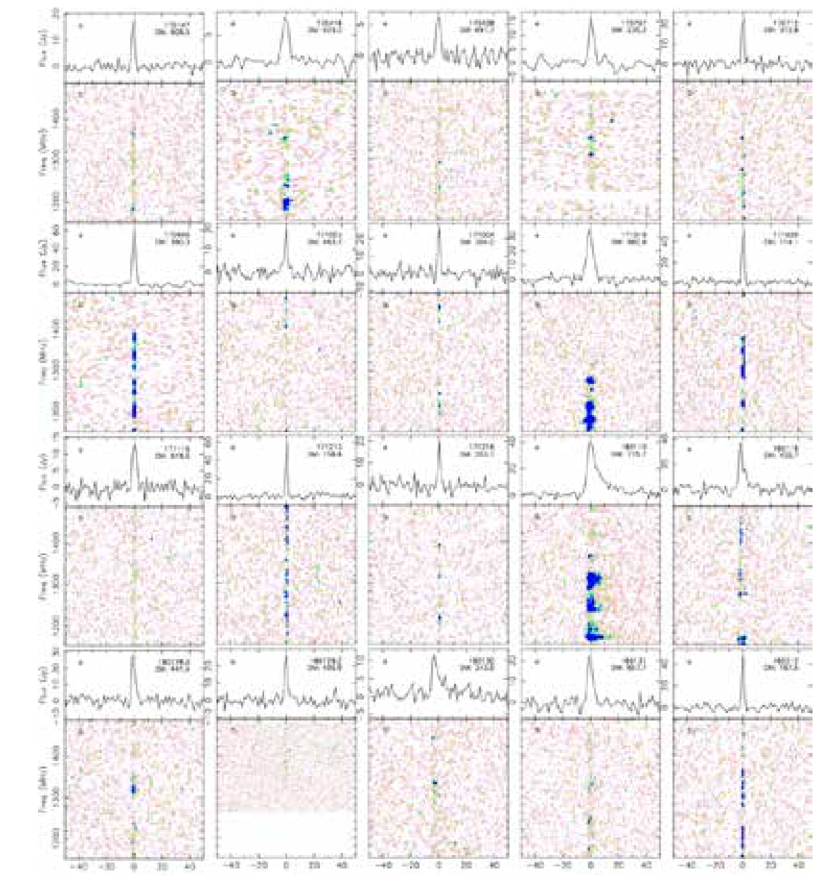
These extreme events are called fast radio bursts, or FRBs for short. The first fast radio burst was discovered in 2007, and was so bright that many astronomers initially dismissed it as an observational error. The next ten years saw about two dozen more fast radio bursts discovered.

Then in 2018, a study using a CSIRO radio telescope in Western Australia almost doubled the known number of these mysterious events. The research team used the Australian SKA Pathfinder (ASKAP) to discover 20 fast radio bursts in one year, including the closest and brightest bursts ever detected. The research, published in the journal Nature, also proved that fast radio bursts come from the other side of the Universe, rather than from our own galactic neighbourhood.

ICRAR astrophysicist Dr Jean-Pierre Macquart, who co-authored the ASKAP study, said the bursts are perfect for detecting matter between galaxies. "Fast radio bursts travel for billions of years and occasionally pass through clouds of gas," he said. "Each time this happens, the different wavelengths that make up a burst are slowed by different amounts."

"Eventually, the burst reaches Earth with its spread of wavelengths arriving at the telescope at slightly different times, like swimmers at a finish line. Timing the arrival of the different wavelengths tells us how much material the burst has travelled through on its journey. And because we've shown that fast radio bursts come from far away, we can use them to detect all the missing matter located in the space between galaxies—which is a really exciting discovery."

While ASKAP was searching for fast radio bursts, another radio telescope—the Murchison Widefield Array (MWA)—was scanning the sky alongside it. Both telescopes were able to capture the same view because they are located side-by-side in the desert of Western Australia's remote Murchison region. Where ASKAP detected several extremely bright fast radio bursts, the MWA—which scans the sky at lower frequencies—did not see anything.



ICRAR astronomer Dr Marcin Sokolowski, who led the MWA research, said the fact that the fast radio bursts were not observed at lower frequencies was highly significant. "When ASKAP sees these extremely bright events and the MWA doesn't, that tells us something really unexpected is going on," he said. "Either fast radio burst sources don't emit at low frequencies, or the signals are blocked on their way to Earth."

Because fast radio bursts are unpredictable, catching them when both telescopes are looking in the same direction isn't easy. It took months of ASKAP and the MWA co-tracking the same area of sky for the researchers to catch the enigmatic bursts. "It's really thrilling to have a clue about the origins of these incredible bursts of energy from outside our galaxy," Dr Macquart said. "The MWA adds an important piece of the puzzle and it was only made possible with this 'technological tango' between the two telescopes." The MWA research was one of five auxiliary papers published in the wake of the ASKAP work.

The discoveries followed research involving another ICRAR scientist—Dr Charlotte Sobey—that was published in Nature earlier in 2018. Dr Sobey was looking at one fast radio burst in particular, known as FRB 121102. The team used data from the Arecibo Observatory in Puerto Rico and the Green Bank Telescope in West Virginia to show that FRB 121102 is in an astonishingly extreme and unusual environment.

The work suggested that the burst was close to a massive black hole, or within a nebula of unprecedented power. But FRB 121102 has a curious habit—it was the first fast radio burst found to repeat.

And that has some astronomers thinking it could be caused by something completely different to the majority of the fast radio burst population.

Dr Macquart said that while the ASKAP study showed fast radio bursts originate from about halfway across the Universe, it didn't tell us what causes them or which galaxies they come from. The team is busy pinpointing the locations of the bursts on the sky, and hopes to localise them to better than a thousandth of a degree. That's about the width of a human hair seen ten metres away, and good enough to tie each burst to a particular galaxy.

Researcher Profile

"I really like that expansive thinking. It's nice to be able to spend my days trying to solve problems like that."

Associate Professor Cathryn Trott
ARC Future Fellow

Associate Professor Cathryn Trott has a warning for students wanting to work with her to detect the faint signals from the early Universe—you realise this is a tricky one.

Cathryn studies the first billion years of the Universe, starting from a time when everything was dark.

"There were no stars in the galaxies and the Universe was opaque," she said.

"And then during this period, the very first stars in the galaxies formed, turned on and they started illuminating the Universe.

"We started getting these bright points of light—and this is called cosmic dawn."

During this time, the hydrogen that filled the Universe was torn apart—split into protons and electrons—and the Universe was reionised.

At the end of the billion years, we were left a Universe that resembles the one we see today.

"Although this was a period of great change, we don't actually have very strong observational evidence of what happened when, and how quickly things evolved," Cathryn said.

"So we try to use radio telescopes to detect the hydrogen and trace this evolution of structure in the early Universe."

The signals from this time are very weak, and figuring out how to detect them is one of the most difficult challenges in astronomy today.

But Cathryn, who previously worked in medical imaging physics, loves that it allows her to think very openly about a problem.

"I spend a lot of my time thinking about really big questions and trying to work out how to approach them," she said.

"I really like that expansive thinking. It's nice to be able to spend my days trying to solve problems like that."

Researcher Profile

"So we can build a picture of how galaxy properties and the processes affecting them have changed over the history of the Universe."

Dr Luke Davies
WAVES Project Scientist

Astrophysicist Dr Luke Davies is trying to understand how galaxies have evolved over the last 11 billion years.

Luke and his colleagues create huge three-dimensional maps of the Universe with observations from optical telescopes.

They then overlay these maps with observations at other wavelengths from the ultraviolet, infrared and radio, using data from some of the world's largest telescopes, including precursors to the Square Kilometre Array.

This allows Luke to study many properties of galaxies such as how many stars they have, how many new stars they are forming, and how much dust and gas they contain.

He can then look at what happens to these properties when galaxies collide, how the location of a galaxy affects its stars and gas, and how dark matter is distributed in the Universe.

"Because it takes a very long time for light to reach us, the further you look into the Universe, the further you look back in time," Luke said.

"So we can build a picture of how galaxy properties and the processes affecting them have changed over the history of the Universe."

Luke leads two international telescope surveys, each involving large teams of scientists from around the world.

The first—the DEVILS survey—uses the Anglo-Australian Telescope to observe approximately 60,000 galaxies and work out their positions in the Universe.

The second—the WAVES-Deep survey—will cover ten times the area of DEVILS, observing nearly a million galaxies using a European Southern Observatory (ESO) telescope called 4MOST.

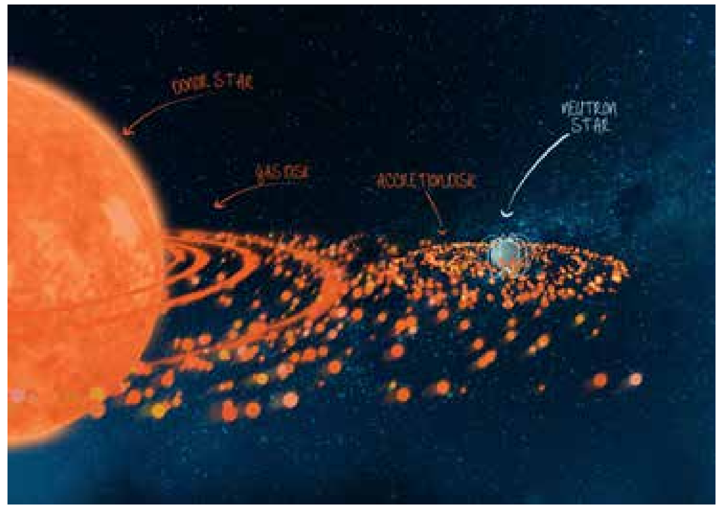
Luke moved to Western Australia from the UK five years ago, attracted by the sunshine and ICRAR's reputation as an exciting young research institution.

He has been a passionate supporter of outreach programs, taking part in countless school and public astronomy events, and has shared a stage with world-famous science communicator Dr Neil deGrasse-Tyson and physicist Professor Brian Greene.

Luke won a prestigious Young Tall Poppy Science Award in 2018.

Neutron star jets shoot down theory

ICRAR and University of Amsterdam researchers detected radio jets belonging to a neutron star with a strong magnetic field—something not predicted by current theory.



Neutron Star and Donor. An artist's impression of the binary system Swift J0243.6+6124. A binary system with a neutron star in a 27-day orbit and a more massive, rapidly-rotating donor star. The rapid rotation of the donor star throws off a disk of material around the stellar equator. As the neutron star passes through the disk during its orbit, it picks up some of this outflowing gas, which then spirals in towards the neutron star in an accretion disk. Credit: ICRAR/University of Amsterdam.

Neutron Star and Magnetic Field. An artist's impression of the neutron star in Swift J0243.6+6124. The neutron star has a very strong magnetic field which prevents the accretion disk from making it all the way in to the neutron star surface. Some of the gas in the disk is channelled along the magnetic field lines onto the neutron star's magnetic poles, giving rise to X-ray emission that we see as brief, regular pulses of X-rays as the star spins around once every 10 seconds. Credit: ICRAR/University of Amsterdam.

Neutron Star Jet. An artist's impression of the strong magnetic field neutron star in Swift J0243.6+6124 launching a jet. During the bright outburst event in which it was first discovered, the neutron star in Swift J0243.6+6124 was accreting at a very high rate, producing copious X-ray emission from the inner parts of the accretion disk. At the same time, the team detected radio emission with a sensitive radio telescope, the Karl G. Jansky Very Large Array in the USA. By studying how this radio emission changed with the X-rays, we could deduce that it came from fast-moving, narrowly-focused beams of material known as jets, seen here moving away from the neutron star magnetic poles. Credit: ICRAR/University of Amsterdam.

In a study published in Nature in September 2018, the team observed the object known as Swift J0243.6+6124 using the Karl G. Jansky Very Large Array radio telescope in New Mexico and NASA's Swift space telescope.

"Neutron stars are stellar corpses," said study co-author Associate Professor James Miller-Jones. "They're formed when a massive star runs out of fuel and undergoes a supernova, with the central parts of the star collapsing under their own gravity. This collapse causes the star's magnetic field to increase in strength to several trillion times that of our own Sun, which then gradually weakens again over hundreds of thousands of years."

University of Amsterdam PhD student Jakob van den Eijnden, who led the research, said neutron stars and black holes are sometimes found in orbit with a nearby "companion" star. "Gas from the companion star feeds the neutron star or black hole and produces spectacular displays when some of the material is blasted out in powerful jets travelling at close to the speed of light," he said.

Astronomers have known about jets for decades, but until now they had only observed jets coming from neutron stars with much weaker magnetic fields. The prevailing belief was that a sufficiently strong magnetic field prevents material getting close enough to a neutron star to form jets.

"Black holes were considered the undisputed kings of launching powerful jets, even when feeding on just a small amount of material from their companion star," van den Eijnden said. "The weak jets belonging to this neutron star only became bright enough to see when the star was consuming gas from its companion at a very high rate.

"The magnetic field of the neutron star we studied is about 10 trillion times stronger than that of our own Sun, so for the first time ever, we have observed a jet coming from a neutron star with a very strong magnetic field. The discovery reveals a whole new class of jet-producing sources for us to study," he said.

Astronomers around the world study jets to better understand what causes them and how much power they release into space. "Jets play a really important role in returning the huge amounts of gravitational energy extracted by neutron stars and black holes back into the surrounding environment," Associate Professor Miller-Jones said. "Finding jets from a neutron star with a strong magnetic field goes against what we expected, and shows there's still a lot we don't yet know about how jets are produced."

Astronomers discover galaxies spin like clockwork

ICRAR astronomers discovered that all galaxies rotate once every billion years, no matter how big they are.

The Earth spinning around on its axis once gives us the length of a day, and a complete orbit of the Earth around the Sun gives us a year. "It's not Swiss watch precision," said ICRAR Professor Gerhardt Meurer. "But regardless of whether a galaxy is very big or very small, if you could sit on the extreme edge of its disk as it spins, it would take you about a billion years to go all the way round."

Professor Meurer said that by using simple maths, you can show all galaxies of the same size have the same average interior density. "Discovering such regularity in galaxies really helps us to better understand the mechanics that make them tick—you won't find a dense galaxy rotating quickly, while another with the same size but lower density is rotating more slowly," he said.

Professor Meurer and his team also found evidence of older stars existing out to the edge of galaxies. "Based on existing models, we expected to find a thin population of young stars at the very edge of the galactic disks we studied," he said. "But instead of finding just gas and newly formed stars at the edges of their disks, we also found a significant population of older stars, along with the thin smattering of young stars and interstellar gas."

This Hubble image reveals the gigantic Pinwheel galaxy, one of the best known examples of "grand design spirals", and its supergiant star-forming regions in unprecedented detail. The image is the largest and most detailed photo of a spiral galaxy ever released from Hubble. Credit: ESA/NASA.

"This is an important result because knowing where a galaxy ends means we astronomers can limit our observations and not waste time, effort and computer processing power on studying data from beyond that point," said Professor Meurer. "So because of this work, we now know that galaxies rotate once every billion years, with a sharp edge that's populated with a mixture of interstellar gas, with both old and young stars."

Professor Meurer said that the next generation of radio telescopes, like the soon-to-be-built SKA, will generate enormous amounts of data, and knowing where the edge of a galaxy lies will reduce the processing power needed to search through the data. "When the SKA comes online in the next decade, we'll need as much help as we can get to characterise the billions of galaxies these telescopes will soon make available to us." The research was published in The Monthly Notices of the Royal Astronomical Society in March 2018.

"To be part of a team of people with different areas of expertise, across several countries but all working together... I think that's beautiful."

Researcher Profile

Claudia Lagos
ASTRO 3D Senior Research Fellow

Theoretical astrophysicist Dr Claudia Lagos loves coming up with fundamental questions about the Universe and trying to solve them.

"Both the questions and the way we're trying to answer them are things I really enjoy," she says. "It's great to have the opportunity to satisfy my curiosity."

Claudia is an expert in galaxy formation and evolution.

She uses computer simulations to understand how the cosmic web, the largest structures in the Universe and the galaxies within them came to be.

"We're trying to understand the processes that give rise to the properties we observe in galaxies," she says.

"Since galaxies have all different kinds of shapes and they live in different environments, the idea is to really take it down to the physics that give rise to those features.

"That's why simulations are so helpful because they allow us to experiment by changing some processes to see whether it gives us a better representation of the real Universe.

"It's a good way of pinpointing what's most important."

Claudia was born in Chile, did her PhD in the UK and worked at the European Southern Observatory in Germany before landing at ICRAR four years ago.

She loves the teamwork that goes into solving some of the mysteries of the Universe.

"These questions are so big, that it's very rare that someone can answer them by themselves," Claudia said.

"To be part of a team of people with different areas of expertise, across several countries but all working together... I think that's beautiful."

"The opportunity to do something fresh from scratch has been refreshing and really that's what's paying dividends right now,"

Researcher Profile

Associate Professor Jean-Pierre Macquart
Senior Research Fellow

Every morning, Associate Professor Jean-Pierre Macquart goes into work and pits his mind against the Universe.

"Usually I come off second best," he laughed.

"But every now and again, you have some little flash of insight into what's going on, and I think that's great."

Jean-Pierre studies the intergalactic medium—the matter in the space between galaxies.

"It's an important thing, because that's where most of the ordinary matter that you and I are made of resides in the Universe," he said.

"So we're doing our best to address a cosmic embarrassment because something like 80 per cent of the baryonic matter is in the intergalactic medium and we don't really know how it's distributed."

One of the biggest things exciting Jean-Pierre at the moment is discovering fast radio bursts, or FRBs.

These mysterious flashes of radio waves from deep space involve incredible energy, and can be used to 'weigh' the intergalactic medium.

Astrophysics has taken Jean-Pierre all over the world, from a PhD at the University of Sydney to research positions at the University of Groningen in the Netherlands and the US National Radio Astronomy Observatory (NRAO).

But it was while working for Caltech that his interest in fast radio bursts began.

"The first detection was announced and it piqued my interest straight away," Jean-Pierre said.

"Because I realised what fantastic probes of intergalactic space these things could be."

Jean-Pierre moved to ICRAR ten years ago, lured by the SKA telescope and a clean research slate.

"The opportunity to do something fresh from scratch has been refreshing and really that's what's paying dividends right now," he said.

"These projects take time to come to fruition, but when they do you have achieved something rewarding that hopefully makes a big difference to our understanding of the Universe."

MWA telescope tunes in on interstellar visitor

The MWA radio telescope was used to observe a mysterious cigar-shaped object that entered our Solar System in late 2017.

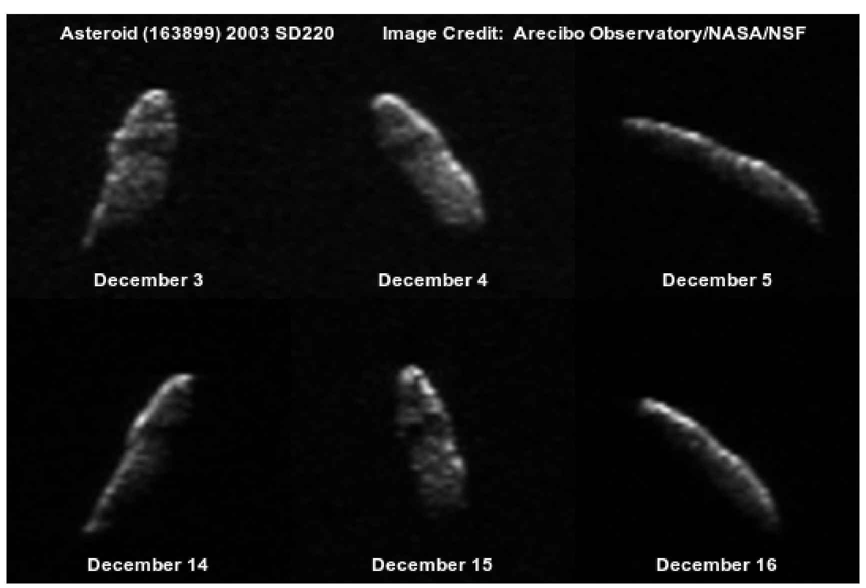
This artist's impression shows the first interstellar asteroid: `Oumuamua. Credit: ESO/M. Kornmesser.

Observations of the first interstellar asteroid: `Oumuamua. Credit: Arecibo Observatory/NASA/NSF.

The first interstellar asteroid: `Oumuamua. Credit: NASA.

The unusual object—known as 'Oumuamua—came from another solar system, prompting speculation it could be an alien spacecraft. ICRAR astronomers went back through the MWA's observations to check for radio transmissions coming from the object between the frequencies of 72 and 102MHz —similar to the frequency range in which FM radio is broadcast.

While they did not find any signs of intelligent life, the research helped expand the search for extra-terrestrial intelligence (SETI) from distant stars to objects closer to home. When 'Oumuamua was first discovered, astronomers thought it was a comet or an asteroid from within the Solar System. But after studying its orbit and discovering its long, cylindrical shape, they realised 'Oumuamua was neither and had come from interstellar space. Telescopes around the world trained their gaze on the mysterious visitor in an effort to learn as much as possible before it headed back out of the Solar System.



John Curtin Distinguished Professor Steven Tingay said the MWA team did not initially set out to find 'Oumuamua. "We didn't set out to observe this object with the MWA but because we can see such a large fraction of the sky at once, when something like this happens, we're able to go back through the data and analyse it after the fact," he said.

"If advanced civilizations do exist elsewhere in our galaxy, we can speculate that they might develop the capability to launch spacecraft over interstellar distances and that these spacecraft may use radio waves to communicate," Professor Tingay said. "Whilst the possibility of this is extremely low, possibly even zero, as scientists it's important that we avoid complacency and examine observations and evidence without bias."

Professor Tingay said the research team was able to look back through all of the MWA's observations from November and December 2017 and early January 2018, when 'Oumuamua was between 95 million and 590 million kilometres from Earth. "We found nothing, but as the first object of its class to be discovered, `Oumuamua has given us an interesting opportunity to expand the search for extra-terrestrial intelligence from traditional targets such as stars and galaxies to objects that are much closer to Earth," he said.

'Oumuamua was first discovered by the Pan-STARRS project at the University of Hawaii in October 2017. Scientists have since determined that `Oumuamua is most likely a cometary fragment that has lost much of its surface water because it was bombarded by cosmic rays on its long journey through interstellar space. The research was published in The Astrophysical Journal in April 2018.

Mapping the Magellanic Clouds

An ICRAR-led study used the Murchison Widefield Array (MWA) telescope to observe radiation from cosmic rays in the Large and Small Magellanic Clouds, showing areas of star formation and echoes of past supernovae.

The Magellanic Clouds are fewer than 200,000 light years away and can be seen in the night sky with the naked eye. The MWA was able to map the Large and Small Magellanic Clouds in unprecedented detail as they orbit around the Milky Way. By observing the sky at very low frequencies, astronomers detected cosmic rays and hot gas in the two galaxies and identified patches where new stars are born and remnants from stellar explosions can be found.

ICRAR astrophysicist Professor Lister Staveley-Smith said cosmic rays are very energetic charged particles that interact with magnetic fields to create radiation we can see with radio telescopes. "These cosmic rays actually originate in supernova remnants—remnants from stars that exploded a long time ago," he said.

"The supernova explosions they come from are related to very massive stars, much more massive than our own Sun, and the number of cosmic rays that are produced depends on the rate of formation of these massive stars millions of years ago."

ICRAR astronomer Dr Bi-Qing For, who led the research, said the study found that the rate of star formation in the Large Magellanic Cloud is roughly equivalent to one new star the mass of our Sun being produced every ten years. However, "In the Small Magellanic Cloud, the rate of star formation is roughly equivalent to one new star the mass of our Sun every forty years," she said.

Two weeks after the publication of the paper, another ICRAR-led study was published suggesting that the two Magellanic Clouds may once have had a third companion. The research describes how another 'luminous' galaxy was likely engulfed by the Large Magellanic Cloud some three to five billion years ago.

ICRAR Masters student Benjamin Armstrong, the lead author on the study, said most stars in the Large Magellanic Cloud rotate clockwise around the centre of the galaxy. But, unusually, some stars rotate anti-clockwise. "For a while, it was thought that these stars might have come from its companion galaxy, the Small Magellanic Cloud," Mr Armstrong said. "Our idea was that these stars might have come from a merger with another galaxy in the past."

Mr Armstrong used computer modelling to simulate galaxy mergers. "What we found is that in this sort of merging event, you actually can get quite strong counter-rotation after a merger takes place," he said. "This is consistent with what we see when we actually observe the galaxies."

A red, green, blue composite image of the Large Magellanic Cloud made from radio wavelength observations at 123MHz, 181MHz and 227MHz. At these wavelengths, emission from cosmic rays and the hot gases belonging to the star forming regions and supernova remnants of the galaxy are visible. Credit: ICRAR.

The Large Magellanic Cloud photographed using a small telephoto lens and a modified DSLR camera to highlight the red HII molecular clouds. Credit: Andrew Lockwood.

The prototype SKA-low station on Australia's SKA site in the Murchison.

3

ENGINEERING

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Overview

ICRAR's engineering team has delivered a complete prototype station for SKA-low.

In 2017 and 2018, the engineering team successfully built the Aperture Array Verification System, or AAVS—an end-to-end system test for the low frequency part of the SKA. The system is collecting signals from the sky on site in the remote Murchison region, the future home of the SKA.

AAVS consists of 256 individual antennas joined together in a tile, replicating a single station of the SKA telescope. This has allowed researchers to test the technology behind the telescope and the logistics of building it in a challenging environment.

This design work for the SKA has been done in collaboration with the Low-Frequency Aperture Array consortium, a group of institutions around the world including ICRAR, Oxford and Cambridge universities, and ASTRON. The group represents more than 500 engineers and scientists, and has been charged with designing the antennas, on board amplifiers and local processing required for the low frequency part of the SKA.

After four years of work, the consortium reached a significant milestone in 2018 with the Critical Design Review. In this final pre-construction stage, the proposed design is tested against the project's tough engineering requirements before a construction proposal for the telescope can be developed.

The SKA engineering work is now in a phase known as 'bridging'—the time between the design and construction phases of the telescope. ICRAR researchers are currently focused on the challenging task of figuring out how to calibrate the stations, and there are test systems on the horizon to perfect this process.

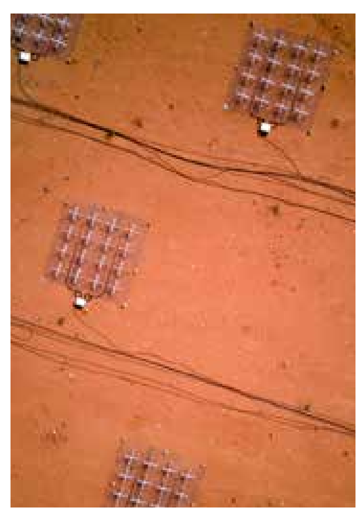
While SKA design work has taken up most of the engineering team's time, the group also played a role in supporting MWA operations. The team is redesigning the MWA's correlator, which takes all the signals from the different antennas and multiplies them together. Individual researchers within the team are also working on smaller projects related to wildlife tagging, infrared systems and antenna modelling techniques.

In the coming years, the engineering team will look more towards translation and impact, making sure industry has the opportunity to capitalise on the expertise ICRAR has developed in designing the SKA. The team's antenna engineering work could find applications in telecommunications, such as 5G technology, and also in satellite systems.

Another field the work could impact is remote sensing, such as space-based systems or radar, for both commercial and military applications. Deep space communication also presents problems very similar to radio astronomy, with very low signal levels over very long distances.

A prototype Transmitter Module from the SKA-mid synchronisation system.

Antenna tiles of the Murchison Widefield Array telescope.



— Feature —

First SKA prototype station completed on site

After a challenging two years, ICRAR's engineering team and their collaborators have successfully built a demonstration SKA station in the Murchison desert.

Known as the Aperture Array Verification System, or AAVS, the system has 256 antennas and replicates one of the 512 stations that will make up the first phase of the SKA.

The system was first deployed in March 2017 but when it was switched on—as for any prototype—there were a few problems. Some of the antennas had a feedback loop and were resonating. After an investigation by ICRAR and the Centre's partners overseas, a solution was devised and the team travelled to the site in November 2017 to fix the problem.

The next challenge was bootstrapping the telescope so signals from all 256 antennas could be combined electronically. "The first stage of bootstrapping the system was to try to grab snippets of data and do some really basic interferometry on a strong radio source—in our case we used the Sun," said ICRAR Associate Professor Randall Wayth. "We transformed the signals from the Sun into a standard radio astronomy data format and then used some of our radio astronomy tools to check if it was behaving in the way we expected."

The bootstrapping process confirmed the signals were coming through the system correctly and identified a couple of malfunctioning antennas that needed to be fixed. "That was one of the biggest hurdles to overcome," Associate Professor Wayth said. "Because now we could take data and process it in a standard radio astronomy way."

In the full SKA, the signals from all the antennas in a station will be combined, working as a single large collecting area—or one big antenna. But in order to commission the station, it is instead run as a mini radio telescope with 256 antennas over a very small area.

Associate Professor Wayth said running the station as a mini telescope meant the researchers were able to fully characterise all of the antennas in the system and check whether it can produce images from the sky. They could check how stable the antenna gains were, and if they changed in the scorching heat of the Murchison.

Aerial view of the prototype SKA-low station at the MRO.

"One of the overarching goals we were trying to achieve is to make sure that we can calibrate the station in a standalone sense," Associate Professor Wayth said.

"Even though the stations in the full SKA are all joined together, one of the requirements is that they need to be able to get into a state where they can be added into the array in a standalone bootstrapping calibration process."

ICRAR operations director Tom Booler said deploying AAVS was a great exercise in teasing out problems before construction commences on the SKA. He said the system was a good scale because, while tiny compared to the full SKA, it was enough antennas to employ realistic production, quality control, packaging and transport processes rather than having every antenna handcrafted in a workshop or lab.

"When we only had 16 antennas, Cambridge University packed them in cardboard and sent them in a plane so they were here in 12 hours," Mr Booler said. "But for AAVS, they spent six weeks on a boat, and so exposed to a corrosive, salty environment, a bunch of them came out rusty. Those kinds of quality control issues don't come up until you exercise a more realistic scale."

Another change in the design because of AAVS was a move from a single power system in the middle of the station to four smaller systems, each supporting a quarter of the array, to reduce the cabling required.

Mr Booler said the experience also helped to tie down realistic estimates of the time it takes to assemble each antenna and do the cabling required on site. "In the SKA context, it's super important to do it at this scale... it teases out a whole bunch of issues that the SKA will have to grapple with and we've learned a lot of detailed lessons," he said.

ICRAR has had a lot of success building telescopes and delivering projects at the SKA site, Mr Booler said. "We've got a team who are super capable of getting bits and pieces on the ground, putting them together, working out why they do or don't work, fixing them and learning lessons from it," he said. "That's what we've brought to SKA over the years and that's why—on the back of AAVS and other work—we're deeply involved in a whole bunch of projects going forward."

Top: An aerial view of the Murchison Widefield Array and prototype SKA-low station on site at the MRO.

Rest: The Prototype SKA-low station with 256 antennas on Australia's SKA site.

"There's not a lot of institutes around the world where you actually get electronic engineers, physicists and cosmologists all working together."

Researcher Profile

Professor David Davidson
Director, Engineering

For Professor David Davidson, electronic engineering is in the blood.

His father worked in telecommunications in the UK and South Africa, and was tasked with creating a microwave link from Pretoria to Cape Town—a distance of about 1500 kilometres.

David's father also worked on radar systems while serving in the British Commonwealth forces in the Middle East and Italy during World War II.

"I grew up with a dad who was an electronic engineer and it just kind of stuck," David said.

David joined ICRAR in 2018 with an impressive CV spanning four continents.

After graduating, he did compulsory national service in the South African Army signals corps, and then worked for the Council for Scientific and Industrial Research in South Africa.

David then spent almost three decades at Stellenbosch University, where his last position was as South African SKA Research Chair at Stellenbosch, working on the MeerKAT radio telescope. During his time at Stellenbosch, he also held several visiting appointments, including at Cambridge University and TU Delft.

Through most of his career, David's main research interest has been computational electromagnetics—the numerical simulation of electromagnetic fields.

This work saw him venture into areas such as whether mobile phones pose risks for human health.

David said engineering is fundamentally about solving problems, and one of the best things about ICRAR is that there are always plenty of challenging problems to get his hands dirty with.

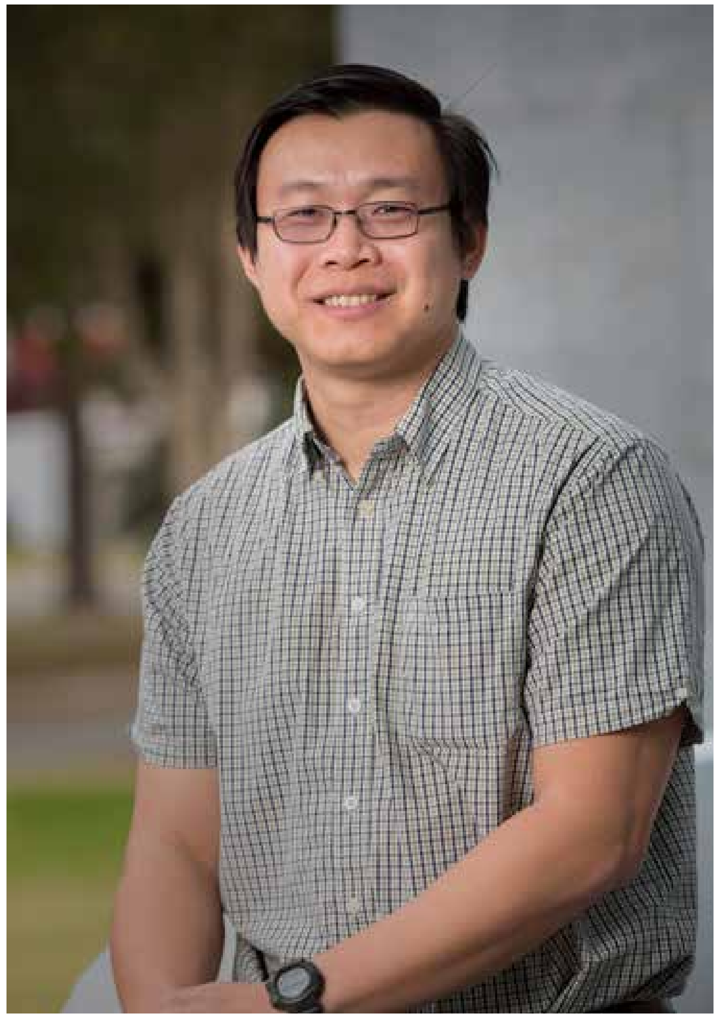
"It's also really interesting working with physicists very closely as we do here," he said.

"There's not a lot of institutes around the world where you actually get electronic engineers, physicists and cosmologists all working together.

"There are so many really smart, exceptional people around… just formidable minds."

"Another thing is the remoteness of the location… we have to plan ahead for all the deployments because it's very difficult to get things if we don't include them in our shipment."

Researcher Profile



Dr Budi Juswardy
Research Engineer

Verifying and characterising the technology for the SKA telescope alongside researchers from Cambridge, Malta and Oxford universities, the Netherlands Institute for Radio Astronomy (ASTRON) and the Italian National Institute for Astrophysics, Dr Budi Juswardy feels lucky to be working with the best in the world.

"It's a pleasure to work with them and with our team here at ICRAR," he said.

Budi is working on the Aperture Array Verification System, the low-frequency portion of the SKA that will be built in Western Australia.

It's part of an ASTRON-led work package that sees Budi visit the remote SKA site in Western Australia's Murchison region up to six times a year.

One of the challenges is to support the consortium's European collaborators to understand the region's extreme conditions.

"It's very dusty, very hot, and the Sun can be quite severe as well," Budi said.

"Another thing is the remoteness of the location… we have to plan ahead for all the deployments because it's very difficult to get things if we don't include them in our shipment."

Budi was born in Indonesia and studied in Singapore.

Before starting at ICRAR eight years ago, he worked in Singapore as an electrical engineer, designing mobile phone handsets.

Budi said he loves contributing to a huge international project with collaborators all over the world.

He also enjoys being at a university because of the opportunity to work with students.

"I've learnt how to engage with undergraduate and research students and impart knowledge," Budi said.

"For me, it's important to engage with students and not have this work confined to the lab."

ICRAR-designed synchronisation system chosen for SKA-mid

An optical fibre-based synchronisation system designed at ICRAR was selected for SKA-mid in South Africa.

One of MeerKAT's 64 antennas that make up the SKA-mid precursor in South Africa's Karoo region. Credit: SKA South Africa.

While optical fibres are incredibly stable and well-suited for transporting digital data, mechanical stresses and thermal changes do affect the fibre, degrading the stability of transmitted timing signals over long distances. The long distances between SKA antennas will mean radio waves from the sky reach each antenna at different times.

With thousands of antennas to be spread over continental scales and therefore thousands of kilometres of fibre, one of the most complex technical challenges for the SKA is to synchronise the incoming signals with extreme precision before they're combined by the SKA's supercomputers.

This is an engineering problem that hasn't been faced before by any astronomical observatory, and the level of precision needed is better than five parts in a trillion. To achieve this level of precision, or "coherence" across the array, the SKA requires a synchronisation distribution system that suppresses these fibre fluctuations in real time.

A team led by ICRAR research fellow Dr Sascha Schediwy, designed a synchronisation system that sends reference signals to each antenna re-using the same optical fibre network that also transports astronomical data to the SKA's central computer. The synchronisation system takes into account the mechanical stresses and thermal changes in the fibre and corrects the timing difference to make sure all signals coming from the antennas are digitised synchronously with a precision better than five parts in a trillion.

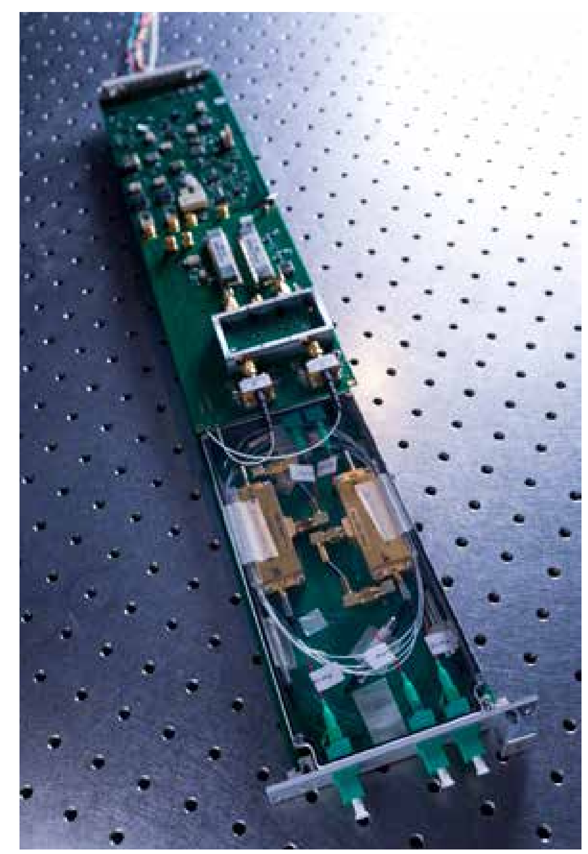
"Our SKA frequency synchronisation system continuously measures changes in the fibre link and applies corrections in real-time with fluctuations of no more than five parts in one-hundred trillion over a 1-second period," Dr Schediwy said.

"A clock relying on a signal of that stability would only gain or lose a second after 600,000 years and field tests have shown our system to be performing between 100 and 10,000 times better than what's required for the SKA."

A close-up of the high-precision electronic microwave-frequency mixing circuitry—a crucial part of every SKA-mid Transmitter Module.

A prototype Transmitter Module shown partly extended from the front of a Sub-Rack enclosure, revealing details of the system's critical fibre-optic components.

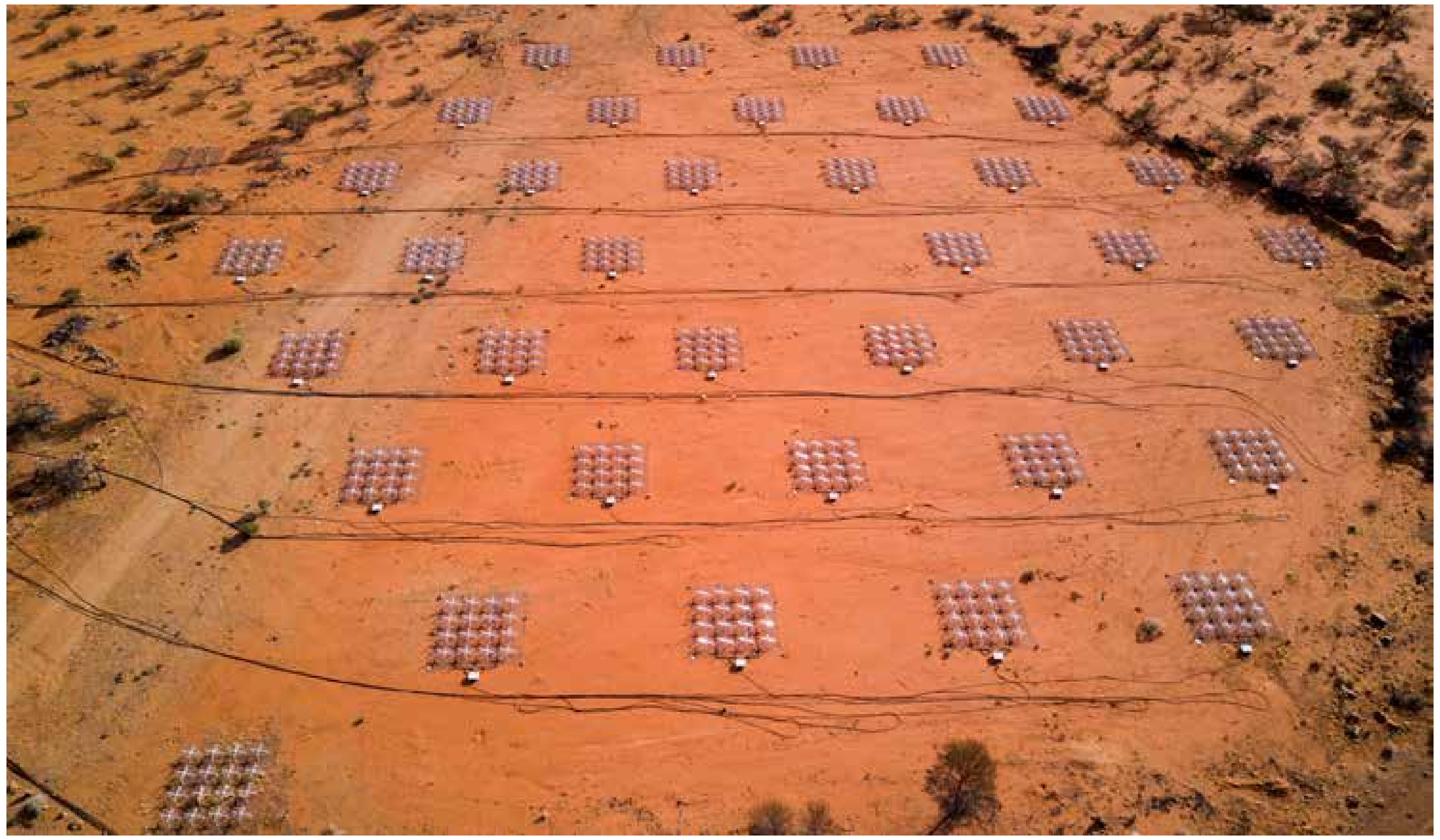
Sascha Schediwy and David Gozzard with components of their SKA-mid phase synchronisation system Transmitter Module.



A prototype Transmitter Module.

The very accurate timing and synchronisation systems will enable the SKA to contribute to many fields from mapping the distribution of hydrogen in the Universe over time, to studying pulsars and detecting gravitational waves on a galactic scale. The technology could also find applications beyond astronomy in areas that require extreme accuracy in transactions, such as currency trading.

The synchronisation system designs chosen were developed as part of the SADT Consortium, led by the University of Manchester. A design by Tsinghua University was selected for SKA antennas in Australia.



Partnership with the defence industry to monitor space

ICRAR teamed up with Adelaide company Silentium Defence to develop a passive radar for the surveillance of objects in space.

Antenna tiles of the Murchison Widefield Array telescope, an SKA Precursor.

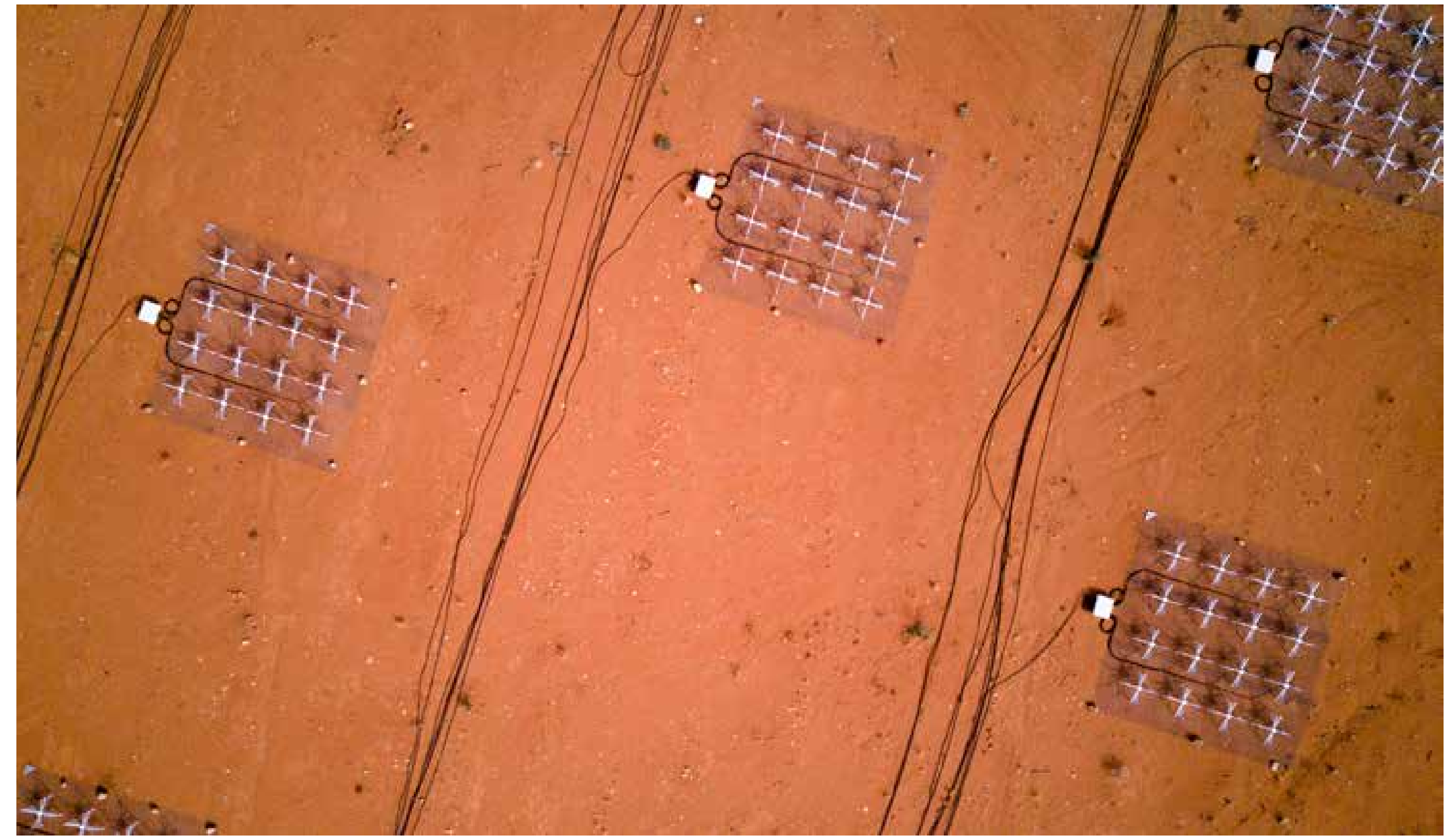
The partnership will see the super-sensitive MWA radio telescope used to record radio waves bouncing off objects in Earth's orbit. These objects can be 1000km away and travelling at up to 8km per second. The signals recorded by the telescope are then processed to create a passive radar. The technique is passive because the radio waves are generated by FM radio stations located around Australia, not from a radar transmitter.

John Curtin Distinguished Professor Steven Tingay said FM radio station broadcasts are carried into space, as well as to car radios, and bounce off objects in orbit around the Earth. "The reflected signals are received by the MWA, and we use them to track the objects," he said. "We can use the radio waves during both day and night, and when it is cloudy, so it can provide 24/7 surveillance in a way that other systems based on optical telescopes cannot."

Surveillance is important to monitor valuable and strategic assets in space and to evaluate the risk of collisions that could destroy multi-billion dollar satellites, including satellites critical for communications. The research team won funding from the Commonwealth Government Defence Innovation Hub, announced in July 2018 by Minister for Defence Industry Christopher Pyne.

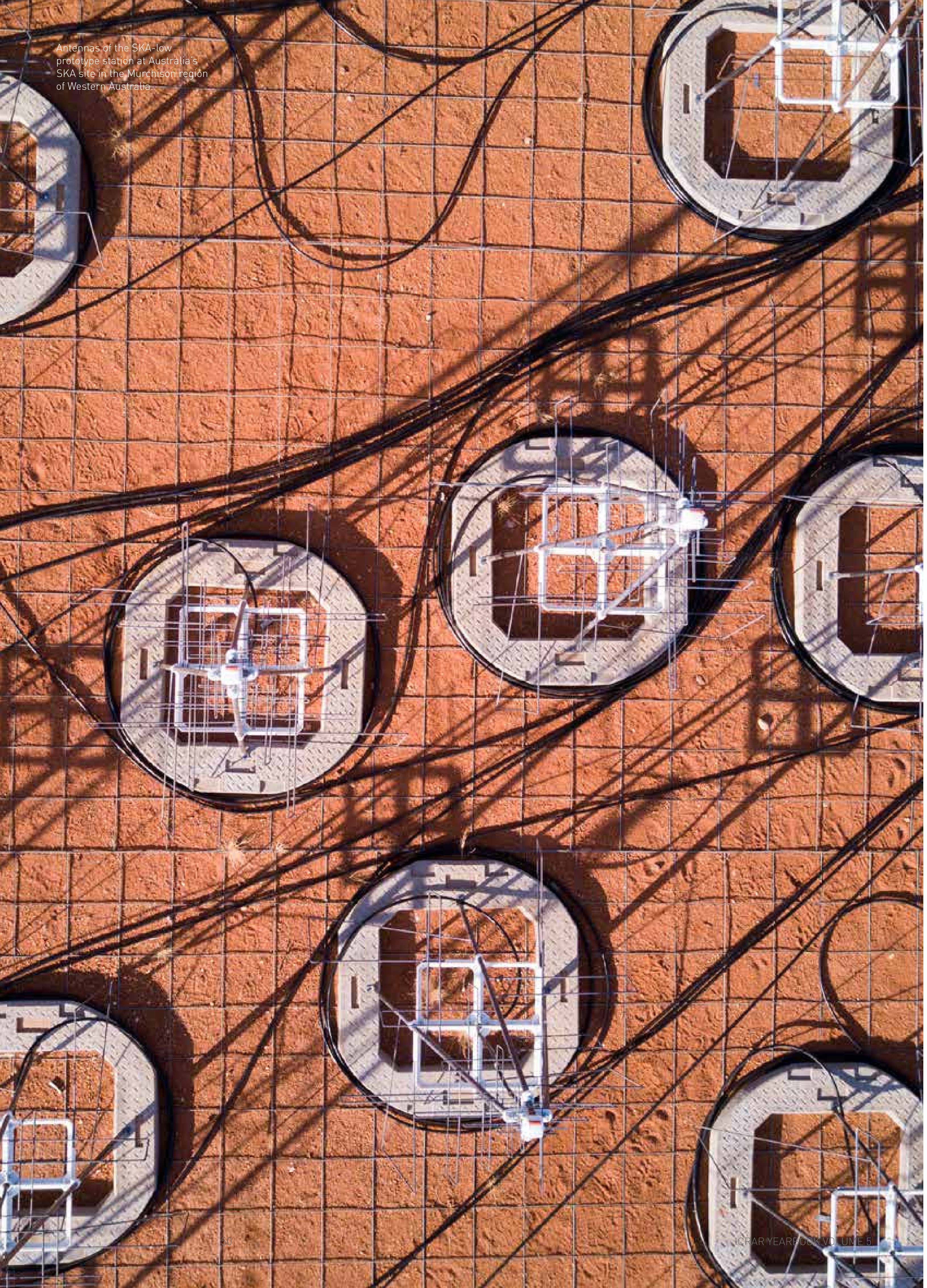
Silentium Defence are experts in passive radar techniques for defence and civilian applications. Coupled with the capabilities of the MWA, the novel combination of industry and academia points to future space opportunities for Western Australia and the nation.

Silentium Defence chief executive Dr James Palmer said the collaboration between Silentium Defence and the ICRAR-Curtin University astronomers with the MWA showed great innovation. "The development of space surveillance capability is a significant activity that Australia can offer to the global space industry," he said.



WA Minister for Science, Innovation and ICT Dave Kelly said the collaboration, supported by both the State and Commonwealth Governments, showed the existing excellence of the space industry in Western Australia and how our investments toward the SKA are paying off outside astronomy.

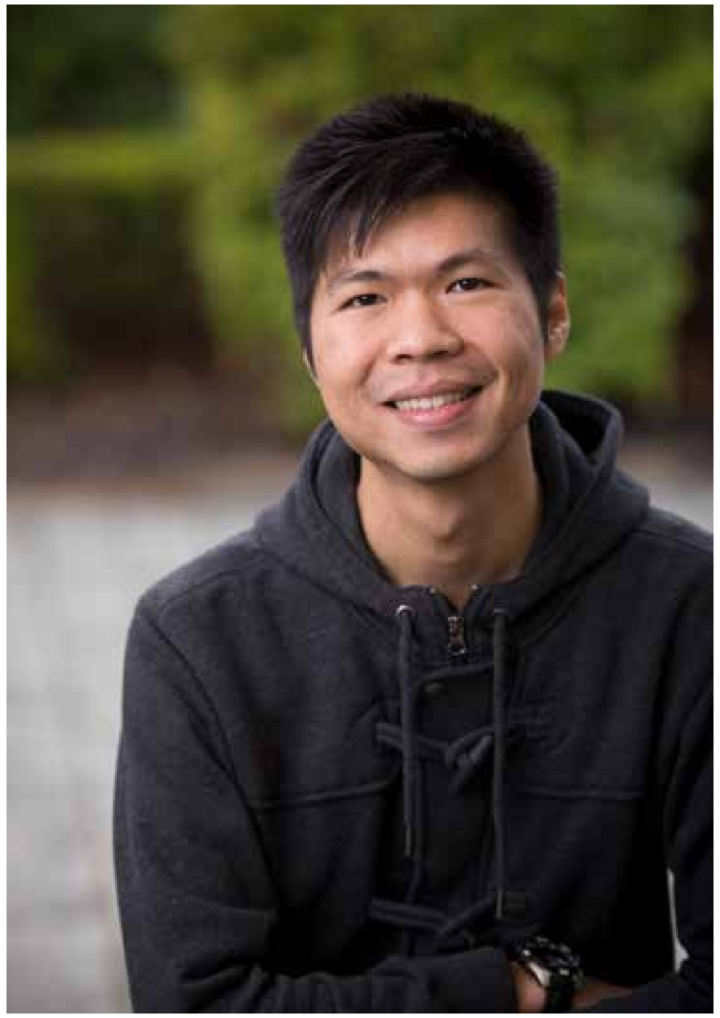
Professor Tingay said radio astronomy in Western Australia has again shown that it has impact well outside of astronomy. "Work like this lays the basis for a more diversified Western Australian economy, with the possibility to tap into the $US350 billion per year global space economy," he said.



Antennas of the SKA-low prototype station at Australia's SKA site in the Murchison region of Western Australia.

“I get to work on a variety of engineering research, and it changes depending on what the SKA demands.”

Key Staff Profile



Daniel Ung
Support Engineer, Aperture Array

The engineering team's research is always shifting—and for Daniel Ung, there's nothing better.

“I get to work on a variety of engineering research, and it changes depending on what the SKA demands,” he said.

“It's not stale, you get new projects coming through and you get to learn new things.”

On a typical day, Daniel might find himself running simulations for the MWA telescope, contributing to the design of the SKA or helping other engineers with their research.

Daniel hadn't considered radio astronomy until he did his final year engineering honours project at ICRAR in 2014.

In 2016, he started his Masters in radio astronomy and at the same time landed a full-time job as a support engineer at ICRAR.

That same year, he won the FEKO Student Competition, a global prize for students working on electromagnetic engineering projects.

For his Masters research, Daniel is analysing the performance of the MWA telescope.

“The quieter your telescope is then the more sensitive it is to detect cosmic signals,” he said.

“My project is about trying to characterise how much noise the telescope is producing.”

Daniel is also working on the design of the SKA telescope and trying to figure out the beam pattern of an SKA station.

He said one of the best things about the job was the people around.

“The people here are nice and very approachable,” he said. “You can have a casual chat, for example, with the director.”

“It makes for a good working environment.”

Chinese Supercomputer Tianhe-2. Image Credit: Prof. Yutong Lu.

4

DATA INTENSIVE ASTRONOMY

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Overview

ICRAR's Data Intensive Astronomy team has played a critical role in shaping the data pipeline for the SKA.

The Data Intensive Astronomy team's big focus for 2017 and 2018 has been the international effort to design the Science Data Processor for the SKA, encompassing the computing hardware platforms, software and algorithms needed to turn signals from the telescope correlator into science data products.

The work is led by Cambridge University and involves more than 40 institutions, including some of the world's top universities. ICRAR's main contribution to the project is the development of an execution framework for the SKA—known as DALiuGE—which will enable researchers to run tens of millions or even hundreds of millions of tasks in just a few hours.

In October 2018, after years of work, the consortium submitted documents for the Science Data Processor Critical Design Review. This key milestone in the project sees the review of the proposed computing infrastructure ahead of the preparation of tender documents for construction of the telescope.

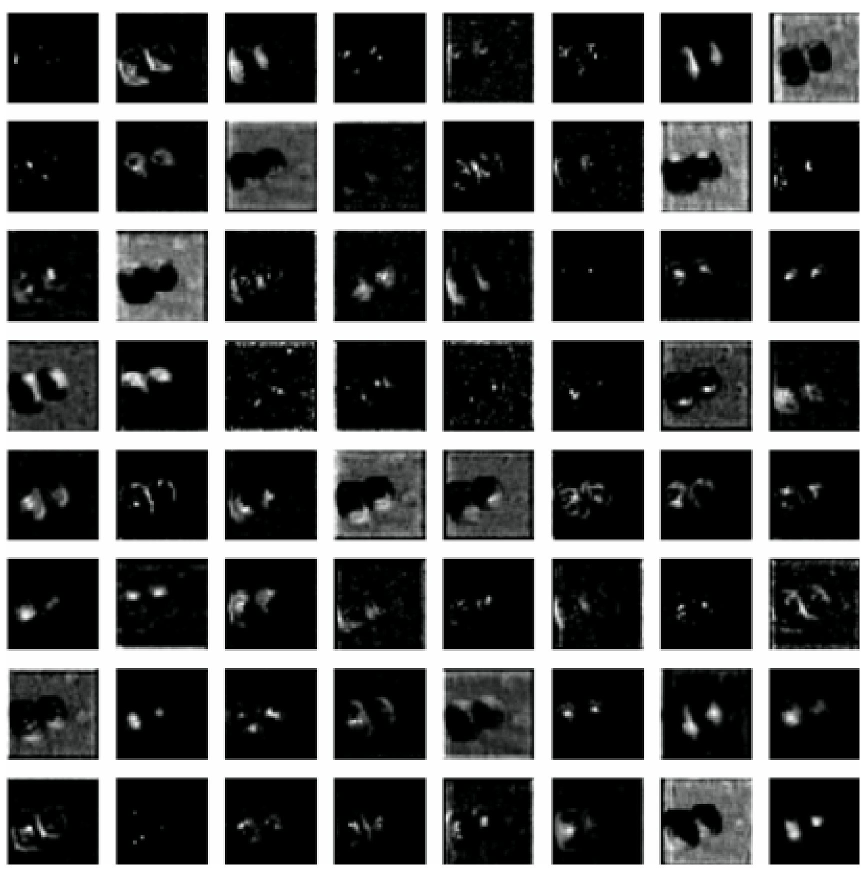
The Data Intensive Astronomy team will continue its strong contribution to the SKA as the telescope enters the next phase of the project, known as 'bridging'. The group will focus heavily on DALiuGE, and the combining of that with the ASKAP data reduction software to produce the JACAL package. The team aims to have JACAL in an operational state within two years, for use on ASKAP, and potentially the MWA, ahead of the first phase of the SKA.

Another highlight has been the receipt of $2 million in funding from CSIRO to conduct a design study for an Australian 'regional centre', which will provide the SKA with the data storage, processing power and people required to enable the scientists to perform the scientific analysis on the high level data products produced by the SKA observatory. This work goes beyond JACAL to create a vision for a whole operations centre and supporting infrastructure, starting with something that will be useful for ASKAP and the MWA.

The Data Intensive Astronomy team continues to support ICRAR's scientists in projects such as the CHILES, DINGO and WALLABY surveys, the latter two of which will make use of the JACAL package. This work is important in helping the team develop capabilities in the management and processing of a variety of big data sets, building the expertise needed to design, construct and operate a regional centre for the SKA.

The team's strong partnerships in China with Shanghai University and the National Astronomical Observatories of the Chinese Academy of Sciences in Beijing are still growing, with several joint workshops held in Australia and China over the last two years. The two countries have teamed up to propose a joint regional centre project—known as ERIDANUS—to process and store data from the SKA. It's one of the many projects coming together as ten years of groundwork begins to pay off for ICRAR, just as construction of the SKA is set to begin in the near future.

The computer-eye view of a Facebook face detection AI bot used to detect radio galaxies.



ICRAR-Nyriad industry partnership could change the future of all storage

The first commercial spin-off from the SKA is revolutionising the way the world manages big data. Nyriad's game-changing technology was developed in partnership with ICRAR on the Murchison Widefield Array (MWA) radio telescope.

— *Feature* —

The ICRAR-Nyriad industry partnership could change the future of all storage.

The first commercial spin-off from the SKA is revolutionising the way the world manages big data. Nyriad's game-changing technology was developed in partnership with ICRAR on the Murchison Widefield Array (MWA) radio telescope.

"We think that this architecture may be the future of all storage," said tech entrepreneur Alex St. John of his company's new product. "We've pioneered a solution that's economically so distinctly more efficient than anything else that's out there."

St. John is the co-founder and chief technology officer of Kiwi start-up Nyriad, the first commercial spin-off from the SKA. He is talking about the company's flagship NSULATE product, a new way of storing data originally developed for the MWA telescope.

The future of all storage? It's a big call. But many seem to agree. Nyriad raised $12 million in venture capital in 2017 and now has more than 100 employees. The company launched NSULATE at the GPU Technology Conference in San Jose in March 2018, where it scored an endorsement from Nvidia founder and chief executive Jensen Huang. But before NSULATE caught the attention of tech royalty, St. John remembers a time when it was just a great idea for the company's first customer—ICRAR.

St. John said Nyriad started when he and cofounder Matthew Simmons met at an SKA colloquium in Auckland. St. John—an expert in GPU computing—and Simmons—an expert in power efficiency and cooling systems—hit it off with a physicist at the conference. The pair were fascinated by the challenges associated with the SKA. St. John, an American expat who created Microsoft's DirectX platform in the 1990s, did some free consulting work on the project.

One of the problems was that the cost of the power needed for the computers was so great, the ten countries involved couldn't support the power bill alone, St. John said. "I was asked, 'what kind of idea would you have to radically change the computer architecture to make it a lot more power efficient?' So Matt and I proposed a new architecture for storage that would eliminate a huge amount of computer infrastructure. [ICRAR's head of data intensive astronomy Professor Andreas Wicenec] and the folks at ICRAR said 'that's a really interesting project, we'll fund it for you guys to build a prototype and see if it works'."

So ICRAR became Nyriad's first customer, helping produce a prototype of the storage architecture. That was successful, and Nyriad went on to build a larger version sponsored by the New Zealand Government under a strategic technology alliance with Australia. The result— known as RABiD—was deployed by ICRAR for the MWA telescope in outback Western Australia.

St. John said the system, which was later commercialised as NSULATE, is a GPU-accelerated storage architecture. This means the same computers doing the supercomputing are also managing their own storage. "By using those supercomputers to manage their own storage locally, we thought we would get rid of all the huge power-hungry and expensive storage fabric that the supercomputer usually requires," St. John said.

If a component fails, the system mathematically error corrects the data across the storage array, making it super resilient, bottle-neck free and very fast. The result is a storage architecture that is faster and cheaper than the current technology.

"Using a GPU, which is a supercomputer, to calculate error correction, allows you to put more drives in parallel," St. John said. "And it allows you to use cheaper, lower-quality drives, because the more drives you put in parallel, the more resilient the array becomes to loss or failures. You can actually use cheaper equipment, and it goes faster at the same time. You get speed and cost efficiency in the same solution."

In late 2018, ICRAR installed the Nyriad software on the MWA cache, a 10-machine cluster at Curtin University. The performance of the software exceeded expectations, and there are plans to go further. The two organisations are hoping to integrate the NSULATE storage capability with the execution framework and software that processes data from the telescope.

St. John said the SKA presents a lot of opportunities for companies to innovate. But he ultimately puts Nyriad's success down to the collision of "crazy tech industry entrepreneurs" and astrophysicists. "Our success is a very unique combination of ICRAR being very receptive and open to working with industry, being really innovative—they really want to tackle new solutions—and happening to encounter some very entrepreneurial start-up people who got involved," he said.

"We think that this architecture may be the future of all storage. We've pioneered a solution that's economically so distinctly more efficient than anything else that's out there."

ICRAR servers running NSULATE

PREVIOUS PAGE

Close up of the Nyriad "Warp Drive", a demonstration system built to showcase Nyriad's NSULATE technology at the Supercomputing Conference in Denver, Colorado, November 2017.

"You can actually use cheaper equipment, and it goes faster at the same time. You get speed and cost efficiency in the same solution."

The prototype "Warp Drive" server built to demonstrate the technology is now being substituted with commercial systems built by storage and server vendor Supermicro.

Co-founder and Chief Technology Officer Alexander St. John presents NSULATE at the Supermicro booth at the 2017 Supercomputing Conference.

Nyriad team with partners Advanced HPC and ThinkParQ, launching the first NSULATE storage server at NVIDIA,Äôs GPU Technology Conference in Silicon Valley, March 2018.

Without ICRAR, Nyriad would not be where it is today, St. John said. "We learned everything we know about it from ICRAR," he said. "Tackling storage and computing problems like this was something I never thought about until I got involved with ICRAR and started understanding the scale and the kinds of computing problems they had. And then I found them fascinating."

"The architecture we've built is really revolutionary, it's very divergent from anything anybody else does in storage. I don't think I ever would have conceived this way if I hadn't been working on such a unique project. We may have invented together the next generation of exascale storage technology."

"The project work is really valued here at ICRAR because it's a big enabler for the science and the astronomers."

Key Staff Profile

Louisa Quartermaine
Project Manager

Louisa Quartermaine's job is to keep researchers all over the planet—from Cambridge University to Perth—on track to deliver key milestones for the SKA telescope.

Half of Louisa's time is dedicated to being the deputy project manager for the Science Data Processor, a package of work that includes the development of the computing hardware platforms, software, and algorithms needed to process science data for the SKA.

The work is led by the University of Cambridge and involves more than 20 institutes and organisations worldwide.

The other half of Louisa's time is allocated to other projects within the Data Intensive Astronomy team, including survey science work and software design.

Louisa started at ICRAR in 2017, after software engineering and project management roles with Motorola and CBH Grain Handling.

She's been able to support the researchers with some of the structure and processes used in industry.

"It's really about the measurement, tracking, and controlling of those projects to make sure things are still ticking along and progressing," she said.

Louisa said she really enjoys working in science and technology.

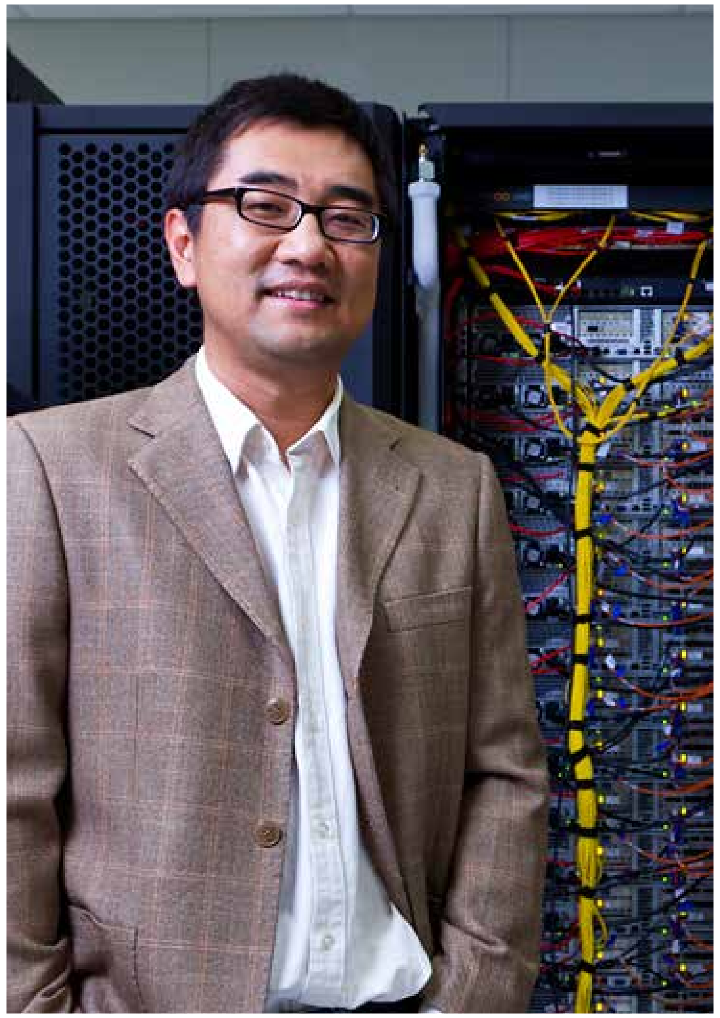
"The project work is really valued here at ICRAR because it's a big enabler for the science and the astronomers," she said.

"And the scale that we work on here in the DIA team is cutting edge.

"A lot of the technology is still being worked on—we're trying to figure out the best way to get all that data down the pipe."

"With careful adaptation and fine-tuning, we can transfer that knowledge from one domain to the next."

Researcher Profile



Dr Chen Wu
Senior Research Fellow

Big data scientist Dr Chen Wu once worked in text mining, doing research like crawling thousands of restaurants reviews to gauge customer sentiment.

It seems a far cry from his current role at ICRAR working with huge astronomy data sets.

But Chen believes they're not so different.

"Essentially they're both signal processing—one is the signals arising from telescopes and the other is signals from human behaviour," he said.

"There are lots of inherent connections between these seemingly unrelated fields.

"For example, the algorithm that Netflix uses to recommend movies to you has also been used for radio interferometry imaging. It's really fascinating for me."

Chen works within the Data Intensive Astronomy team to develop, optimise and operate astronomical data systems.

He looks at the infrastructure needed to manage and process the huge volumes of data coming from next-generation radio telescopes, including the SKA and its precursors.

His work has seen him become part of the international team developing execution framework for the SKA Science Data Processor, and help to manage the data system for the MWA telescope.

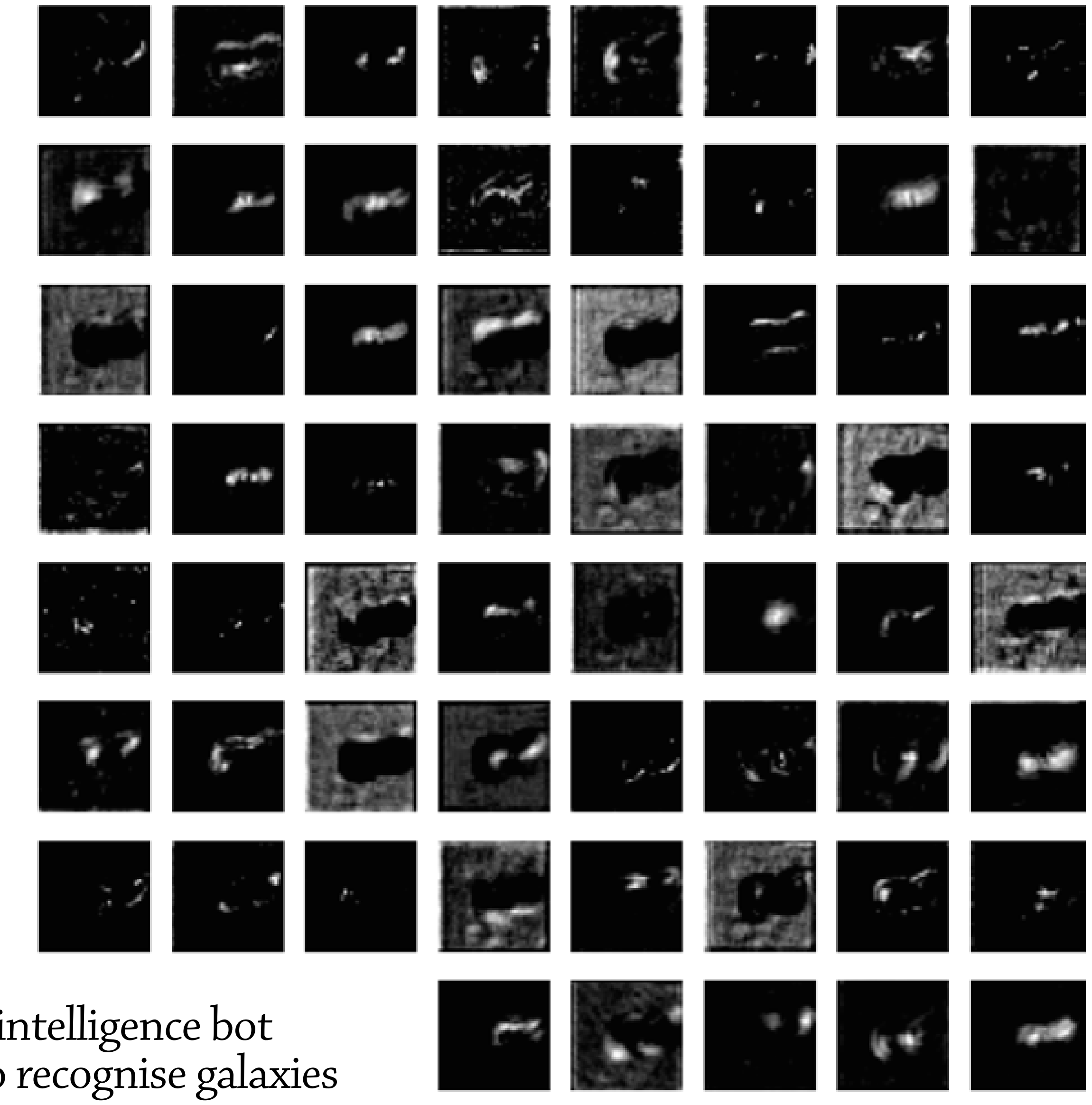
Chen also does research in the area of data science, including machine learning and artificial intelligence.

One of his projects—ClaRAN—modified an artificial intelligence program originally used to recognise faces on Facebook to identify galaxies in deep space.

For Chen, it was a natural fit.

"Detecting human faces is not fundamentally different from detecting objects in the Universe," he said.

"With careful adaptation and fine-tuning, we can transfer that knowledge from one domain to the next."



Artificial intelligence bot trained to recognise galaxies

ICRAR researchers taught an artificial intelligence program used to recognise faces on Facebook to identify galaxies in deep space.

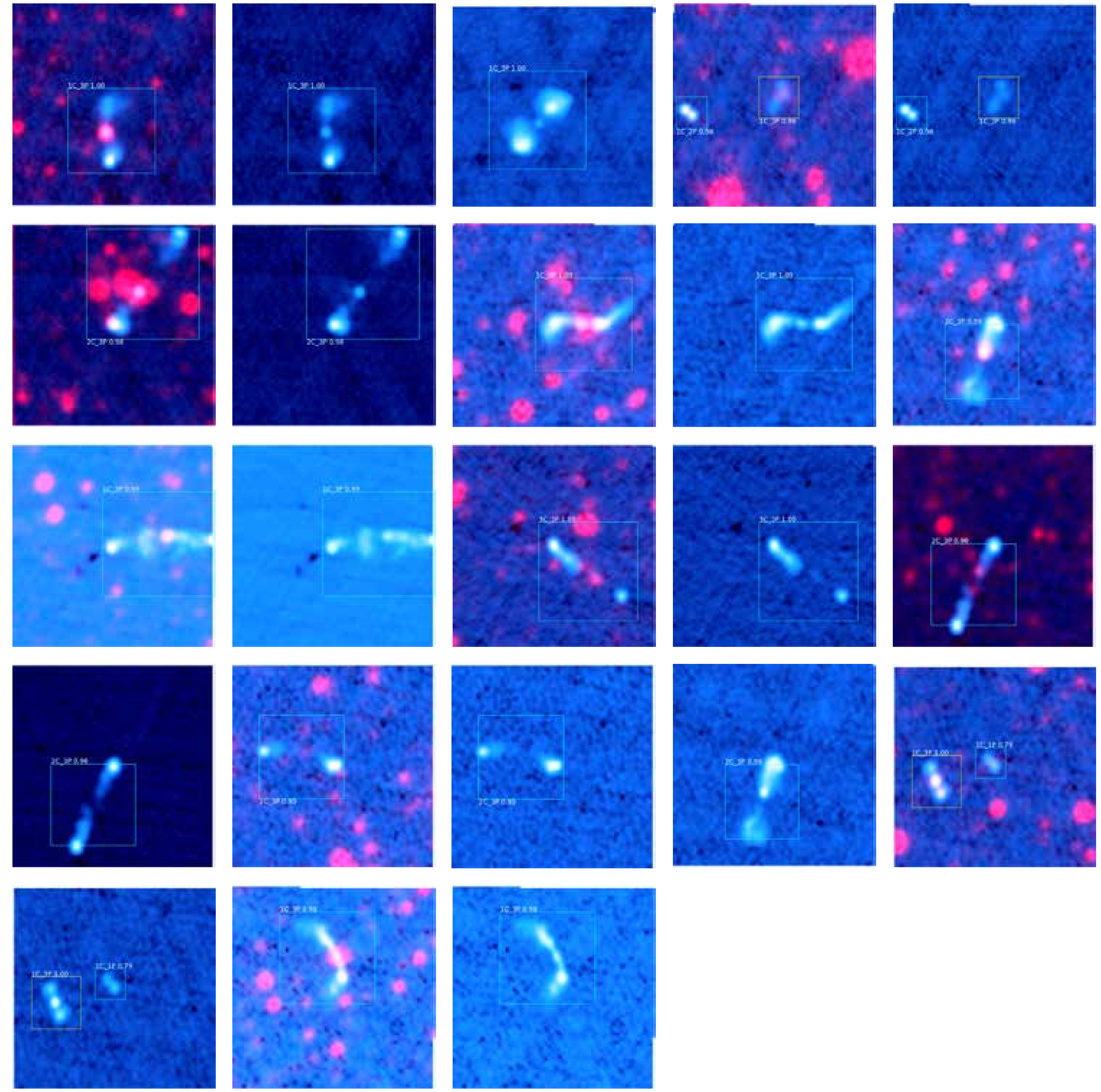
The result is an AI bot named ClaRAN that scans images taken by radio telescopes. Its job is to spot radio galaxies—galaxies that emit powerful radio jets from supermassive black holes at their centres. ClaRAN is the brainchild of big data specialist Dr Chen Wu and astronomer Dr Ivy Wong.

Dr Wong said black holes are found at the centre of most, if not all, galaxies. “These supermassive black holes occasionally burp out jets that can be seen with a radio telescope,” she said. “Over time, the jets can stretch a long way from their host galaxies, making it difficult for traditional computer programs to figure out where the galaxy is. That’s what we’re trying to teach ClaRAN to do.”

Dr Wu said ClaRAN grew out of an open source version of Microsoft and Facebook’s object detection software. He said the program was completely overhauled and trained to recognise galaxies instead of people. ClaRAN itself is also open source and publicly available on GitHub.

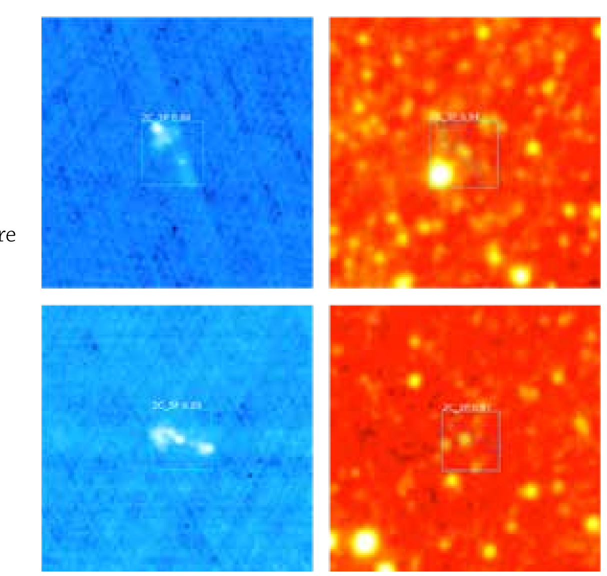
Dr Wong said the upcoming EMU survey using the WA-based Australian Square Kilometre Array Pathfinder (ASKAP) telescope is expected to observe up to 70 million galaxies across the history of the Universe. She said traditional computer algorithms are able to correctly identify 90 per cent of the sources. “That still leaves 10 per cent, or seven million ‘difficult’ galaxies that have to be eyeballed by a human due to the complexity of their extended structures,” Dr Wong said.

Dr Wong has previously harnessed the power of citizen science to spot galaxies through the Radio Galaxy Zoo project. “If ClaRAN reduces the number of sources that require visual classification down to one per cent, this means more time for our citizen scientists to spend looking at new types of galaxies,” she said. A highly-accurate catalogue produced by Radio Galaxy Zoo volunteers was used to train ClaRAN how to spot where the jets originate.



ClaRAN detections of radio galaxies using data from both radio and infrared telescopes.

Dr Wu said ClaRAN is an example of a new paradigm called ‘programming 2.0’. “All you do is set up a huge neural network, give it a ton of data, and let it figure out how to adjust its internal connections in order to generate the expected outcome,” he said. “The new generation of programmers spend 99 per cent of their time crafting the best quality data sets and then train the AI algorithms to optimise the rest. This is the future of programming.” A research paper on ClaRAN was published in October 2018 in Monthly Notices of the Royal Astronomical Society.



‘Regional Centres’ to process and store data for the SKA

Creating a network of ‘regional centres’ to provide the SKA with data storage.

An artist’s impression of the data deluge caused by the next generation of radio telescopes.

Fifteen years ago, the brains behind the Large Hadron Collider realised that while they could build the ring and the detectors that sat on the ring, they couldn’t provide all the computing resources needed to analyse the data from the facility. So the Large Hadron Collider community agreed to provide this infrastructure, and worked with the facility to capture the data and do the science.

In 2016, the SKA Organisation realised the same thing—that the data coming from the telescope would need further processing and long-term storage, outside of the initial scope of the project, to maximise the science outcomes. This got the SKA community thinking about how to create a network of ‘regional centres’ around the telescope, to provide the SKA with the data storage, processing power and people required to create, store and access high-value data products for scientists.

In late 2016, the SKA regional centre coordination group was created, with ICRAR executive director Peter Quinn representing Australia. The group features representatives from all the SKA countries with an interest in creating a data intensive facility that could support the SKA, but also develop big data skills for use in other areas, such as particle physics, medicine or geology.

These regional centres will need to offer enough processing power and storage to push the data from the telescope all the way through to scientific publication. They will also need to be able to curate and manage that data forever, so it can be used for different purposes.

In 2017, a number of international efforts started to emerge around the creation of regional centres. The first, a project known as AENEAS, saw the banding together of several European nations proposing to share a common plan and strucure for regional centres. Shortly after, another project called ERIDANUS was created as a collaboration between Australia and China, proposing a coordinated and connected regional centre in the Asia-Pacific region to share in the SKA science gold rush.

More proposals are now emerging from Canada, South Africa and India.

ICRAR believes regional centres are an important part of the Centre’s future, and has taken the lead on the ERIDANUS project. The Centre’s expertise in this area is based on the strength of the Data Intensive Astronomy group, and the experience the team has gained through SKA precursor projects and design work for the SKA itself.

Over the next three years, ICRAR will undertake a design study for the Australian regional centre, culminating in 2020 with a proposal to the Federal Government for a major investment in data processing and storage for Australia. Initially this regional centre will focus on doing great science with the precursor telescopes—ASKAP and the MWA—and using them as a training ground for the first phase of the SKA.

Key Staff Profile

“Designing and implementing the computing infrastructure to support the world’s largest telescope—who wouldn’t take up such an opportunity.”

Mark Boulton
Senior Systems Engineer and IT manager

When Mark Boulton was offered the chance to be part of the science data processor consortium for the SKA telescope, he jumped at it.

“Designing and implementing the computing infrastructure to support the world’s largest telescope—who wouldn’t take up such an opportunity,” he said.

Mark’s systems engineering role sees him involved in planning what happens to the huge amounts of data that will come from the SKA.

That includes managing how the data is processed, stored and accessed by astronomers.

Mark is also ICRAR’s IT manager, looking after the Centre’s servers, two petabytes of on-site storage and a small compute cluster of about 10 nodes, plus ancillary and support systems.

“That’s basically to provide the researchers with a facility to store data as well as do some computation,” he said.

“It’s set up in such a way as to replicate the basics of the Pawsey Supercomputing Centre, so people can do a little bit of work here and then carry it over to Pawsey and other high performance computing systems around the world.”

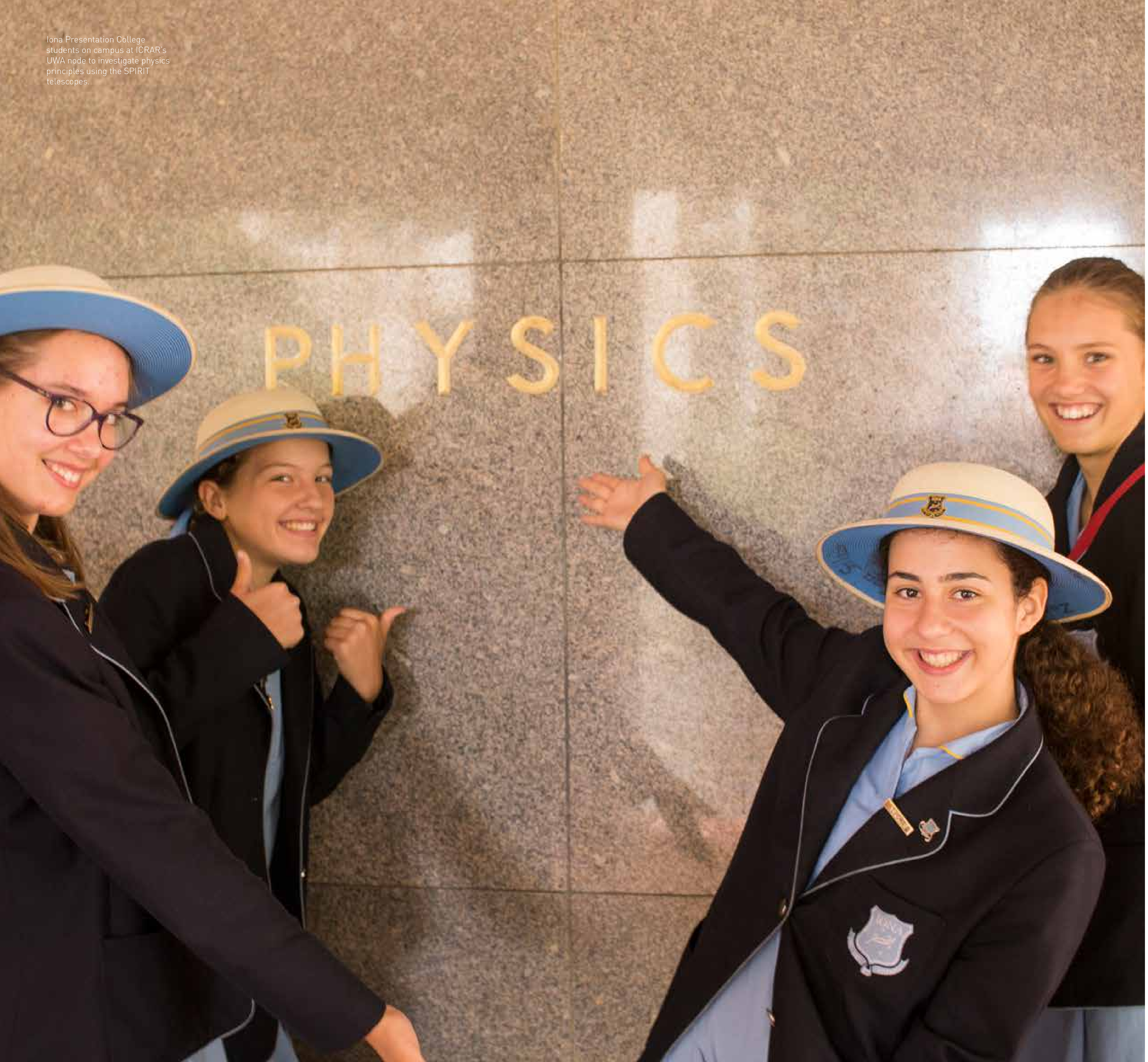
Before coming to ICRAR, Mark was a senior systems engineer at Thales, working on internal infrastructure as well as government and defence contracts.

He designed the front end for Acland Transport’s ticketing system and a wide area network for Queensland Motorways.

One of the challenges of the SKA is that the computing infrastructure will likely be the last part of the telescope to be purchased.

“With computers, as soon as you buy them there’s always going to be something new or better,” he said.

“So you want to buy them as late as possible… but always being mindful of providing adequate time for final tests and integration.”



Iona Presentation College students on campus at ICRAR's UWA node to investigate physics principles using the SPIRIT telescopes.

5

OUTREACH, EDUCATION & COMMUNICATIONS

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Overview

The big questions we ask about the Universe get people talking and the images captured by our telescopes never fails to inspire "wow moments" in young and old alike.

ICRAR's team of expert astronomical science communicators and educators leverage this inherent public interest for astronomy and space to generate awareness of the Square Kilometre Array project, while promoting the Centre's research across Science, Engineering and Data Intensive Astronomy.

Over the past ten years, we've delivered programs to more than 150,000 members of the public, school students and teachers. Our website, social media platforms and innovative Internet based citizen science initiatives reach an audience in excess of 75,000 visitors each year. Our media releases and a commitment to communicating research stories that capture the imagination of a global audience have led to more than 10,000 articles and a readership in the millions.

Through ICRAR's outreach, education and communications (OEC) programs, our objectives are to:

- Promote ICRAR, Curtin University, The University of Western Australia and WA;
- Raise the profile of radio astronomy, the SKA and SKA Pathfinders in Australia;
- Help to attract and retain exceptional researchers;
- Inspire public interest and participation in science, engineering and data intensive research;
- Promote uptake of science, engineering and technology related studies and careers; and
- Support educators in the classroom.

Dr Natasha Hurley-Walker describing the GLEAM survey (shown on screen) in an interview for the BBC's The Sky at Night' program.

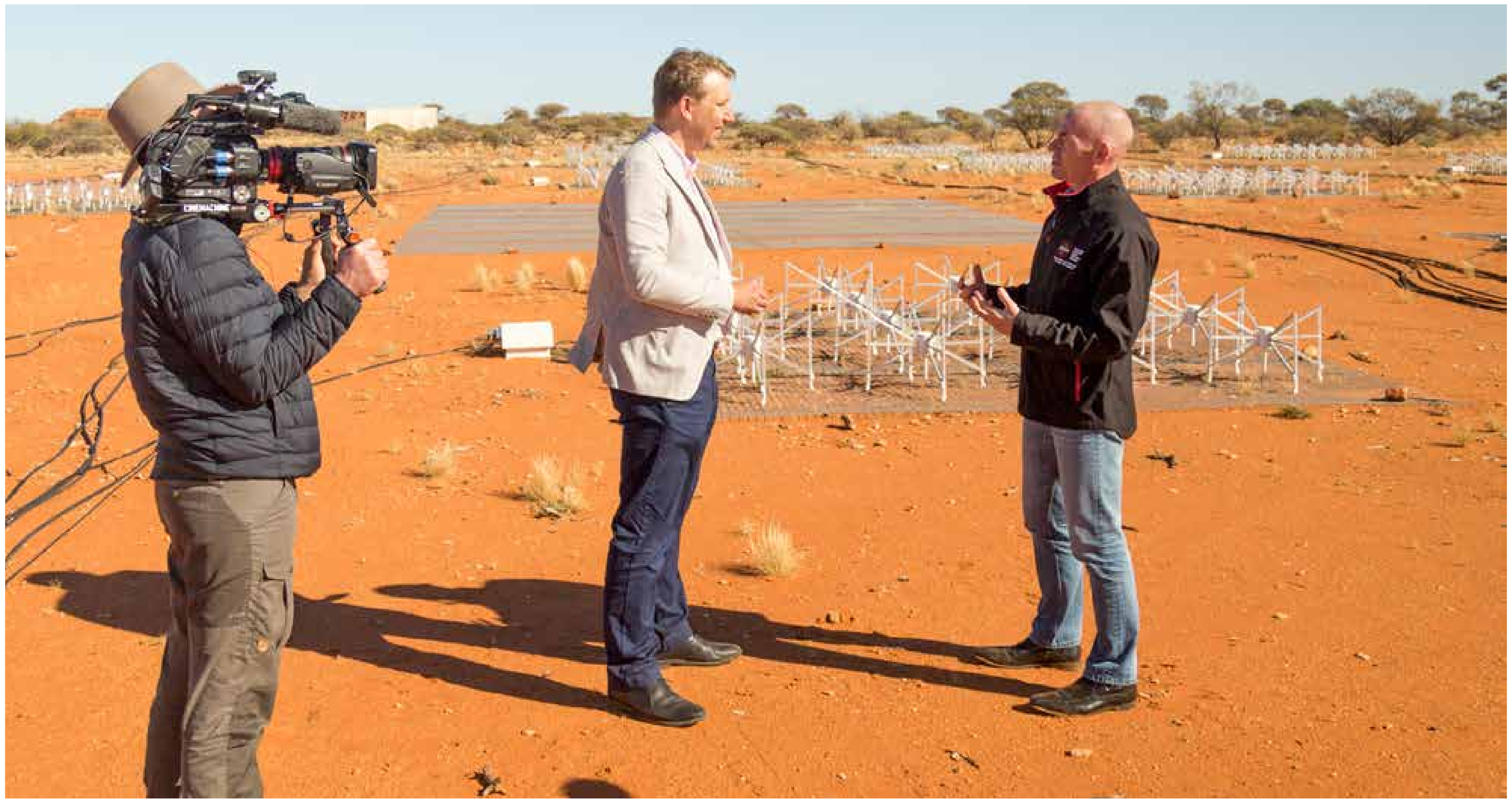
— *Feature* —

In the news

In 2017 and 2018, there were more than 3300 news stories in 75 countries mentioning ICRAR.

Top and Bottom row: Staff and students practising their media engagement skills at the Centre's annual media training.

Middle: Professor Steven Tingay talks about the Murchison Widefield Array to the BBC's cameras for their 'The Sky at Night' program.



In March 2018, ICRAR was approached by the BBC to facilitate filming for an episode of 'The Sky at Night' at the Murchison Radio-astronomy Observatory (MRO). Initially, the producers planned to film only part of the program in Western Australia. But when they saw the video assets ICRAR had captured on site with local production company Red Empire, the BBC producers chose to film an entire episode in Western Australia, shooting in both Perth and at the MRO.

This opportunity put the Murchison Widefield Array telescope, the MRO and SKA Australia in front of a mainstream UK audience of half a million people, and established a working relationship with the BBC in London. The 30-minute show, titled 'Outback Astronomy' aired in the UK in July 2018, and was available online through BBC iPlayer.

The Sky at Night show is just one example of the combination of research excellence, quality in-house media support and strong multimedia assets that have seen ICRAR receive very high levels of media coverage. By distributing releases featuring newsworthy research, engaging writing and high-quality multimedia content—including photographs, graphics, animations and video interviews—ICRAR has developed a reputation for media statements worthy of journalists' time.

The outreach team works hard to cultivate relationships with individual journalists and media organisations over time. They also run media training, social media and presentation skills workshops to support researchers in sharing their science. Through this work, and the talent of ICRAR researchers, the Centre has developed a growing reputation for researchers who are experienced and skilled in dealing with the media, and willing to make time to respond quickly to media enquiries from around the world.

In 2017, ICRAR distributed 13 media releases, and featured in 1400 articles in 65 countries. ICRAR researchers were interviewed on radio by media organisations including ABC, SBS, 6PR, 2GB and 2UE, and on television by programs including Channel 10 News and Lateline.

In 2018, ICRAR distributed 15 media releases, and featured in 1960 articles in 75 countries.

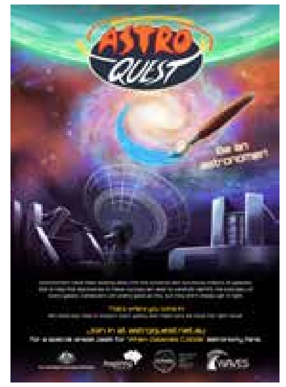
Researchers' broadcast appearances included US National Public Radio, Channel 10, ABC and SBS.

Top media release 2017-2018

Aussie telescope almost doubles known number of mysterious 'fast radio bursts' (300+ articles mentioning ICRAR)

October 11, 2018

Australian researchers using a CSIRO radio telescope in Western Australia have nearly doubled the known number of 'fast radio bursts'— powerful flashes of radio waves from deep space.



Top left: Artists impression of a WAVES galaxy that citizen scientists will help study using AstroQuest.

Inset: The galaxies in AstroQuest's data includes information from multiple telescopes.

Bottom: A timeline of the history of the Universe, showing when light left the galaxies citizen scientists will help study using AstroQuest.

AstroQuest harnesses people power to discover more about galaxies

In 2017, ICRAR received $350,000 in Federal Government funding for an innovative new online citizen science project.

Known as AstroQuest and funded under Inspiring Australia, the project will enlist the help of volunteers to explore galaxies billions of light years away. These citizen scientists will help astronomers with their research by inspecting images of galaxies and deciding whether a computer identified them correctly—all from the comfort of their loungeroom. It's all about using people power to increase the breadth of science that can be done with observations from telescopes.

AstroQuest builds on Galaxy Explorer, a citizen science project developed by ICRAR and ABC Science for National Science Week 2015. In Galaxy Explorer, volunteers were asked to classify galaxies and fit a ring around each one. More than 200,000 galaxies were classified over the duration of the project.

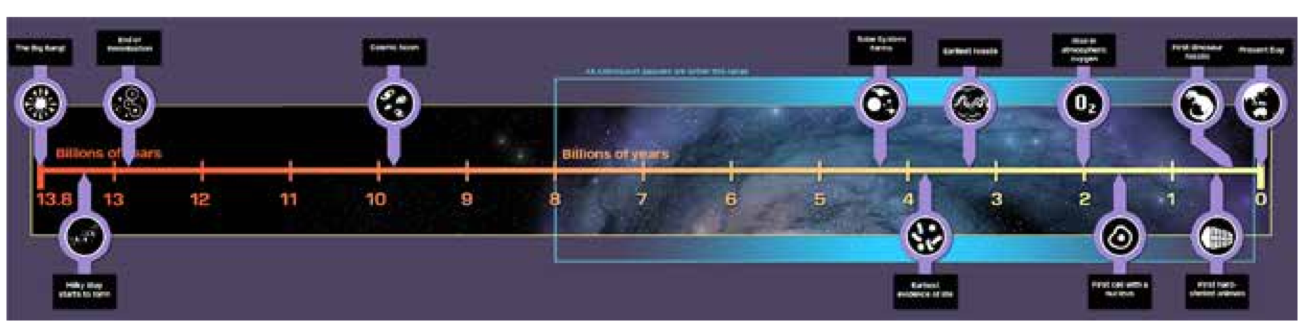
In AstroQuest, citizen scientists will be asked to inspect galaxies between 800 million and 4 billion light-years away. These galaxies are from a huge survey of millions of galaxies. The first step required by astronomers before they can use the survey data is to locate each galaxy in the image and separate it from other galaxies or stars. By doing this, astronomers can work out things like how far away the galaxy is, how many stars it contains, whether they are old or young stars, and how the galaxy is evolving.

The computer algorithm that scientists use to classify these galaxies tries to find the galaxy in the image, and colours in the shape it finds. In a lot of cases, the computer algorithm gets the right result—colouring in the central galaxy in the image with one colour, and any overlapping objects in different colours.

But there are cases where the algorithm doesn't get the right answer. Sometimes it thinks different parts of the same galaxy are actually separate galaxies. Sometimes the computer thinks a galaxy and a star that overlaps it are the same object.

AstroQuesters will be asked to inspect each galaxy, tell astronomers whether the computer got it right, and do their best to fix it if needed. This will help astronomers a lot, as they can use the results to improve the algorithm being used to find galaxies in huge surveys, and even train new machine learning algorithms to do this work better and faster.

AstroQuest is available at astroquest.net.au.



Teachers and students take on real research

Before students at Willetton Senior High School met ICRAR astrophysicist Dr Sarah White, they told their teacher that astronomers were people who stayed up late and looked through telescopes. After engaging with Dr White, they had a different answer; astronomers organise data.

Dr Sarah White, Anusha Appanah-Veerahoo, Dr Michael Fitzgerald and Darren Hamley working on the Australian Teacher Astronomy Research Program.

The Willetton students' teacher Darren Hamley was part of the Australian Teacher Astronomy Research Program, an Edith Cowan University and CSIRO-led project that saw him and Byford Secondary College teacher Anusha Veerahoo mentored by Dr White. Under Dr White's guidance, the two teachers took data from the Murchison Widefield Array (MWA) and the Australia Telescope Compact Array (ATCA) into the classroom, and taught their students how to use it to look for different types of galaxies.

Ms Veerahoo said her Year 9 students were able to play with the program used to analyse the data. "We were trying to get the students to actually change the program a little bit, have a look at how it works, how it's written and how to actually use the data to find objects in the sky," she said.

The idea was to immerse students in the scientific process and what scientists do day-to-day, Dr White said. "By using my current topic… we wanted to get them interested and enthused," she said.

For Ms Veerahoo, it was a chance to reconnect with her studies in physics and computing, with a focus on programming in astronomy. "Astronomy is my background but I haven't touched it since my degree so it was good to get back into it," she said. "But it was also really good to see kids see real applications of science and engineering. It kept them really engaged."

At first, when the students didn't find an immediate conclusion, they thought they'd done something wrong, Dr White said. "We really are studying something brand new and we're just investigating it for the first time, so we don't know what the answer's going to be," she said. "They were used to their teachers always having the answer."

Mr Hamley said his gifted Year 8 students spent weeks poring over the data, despite the complex concepts involved. "It was totally new but I think that made it easier in a way because they didn't have any preconceived ideas," he said. "They found it super rewarding."

Both teachers plan to incorporate the research project into their classes in 2019. "We had about 2000 sources, we did about 200 of them… so we're actually going to try and do more sources this year," Ms Veerahoo said.

At the end of the program, one of Mr Hamley's students said astronomers were the most generous scientists. When he queried the student on why, she said "astronomers use the most expensive scientific equipment, and they let us use it for free!"

SPIRIT program doubles with dark sky additions

Twice as many Western Australian school students are able to access a telescope remotely through the Internet with the addition of two new telescopes to the SPIRIT program.

SPIRIT 3 in its enclosure at Gingin.

SPIRIT 3 & 4 telescopes ready to observe.

SPIRIT 3 donor Neil Shaw with SPIRIT Program Manager Paul Luckas.

The additional telescopes—SPIRIT 3 and SPIRIT 4—are the result of exceptional donations from astronomy-loving individuals.

SPIRIT program manager Paul Luckas said the two telescopes had been installed at UWA's dark sky site at Gingin, one hour north of Perth.

"The telescopes sit alongside the Zadko Observatory, away from light pollution from Perth city," he said,

"Students are able to use the instruments to capture impressive images in all directions, further increasing the potential for research."

As with all SPIRIT telescopes, students book and then remotely access and control the instruments in 'real time' from their home or school computers using a web browser.

Students are able to monitor telescope operations as they capture images of galaxies, nebula and star clusters.

Advanced students and researchers can also collect data while they sleep by uploading observing plans in advance.

Mr Luckas said the SPIRIT program gives Western Australian schools access to the same tools used by professional astronomers to observe and collect astronomical data.

"Students tend to start out using SPIRIT to capture images of astronomical objects," he said.

"They can then progress to using the telescope for real research—things like observing stars that change brightness and submitting their observations for publication.

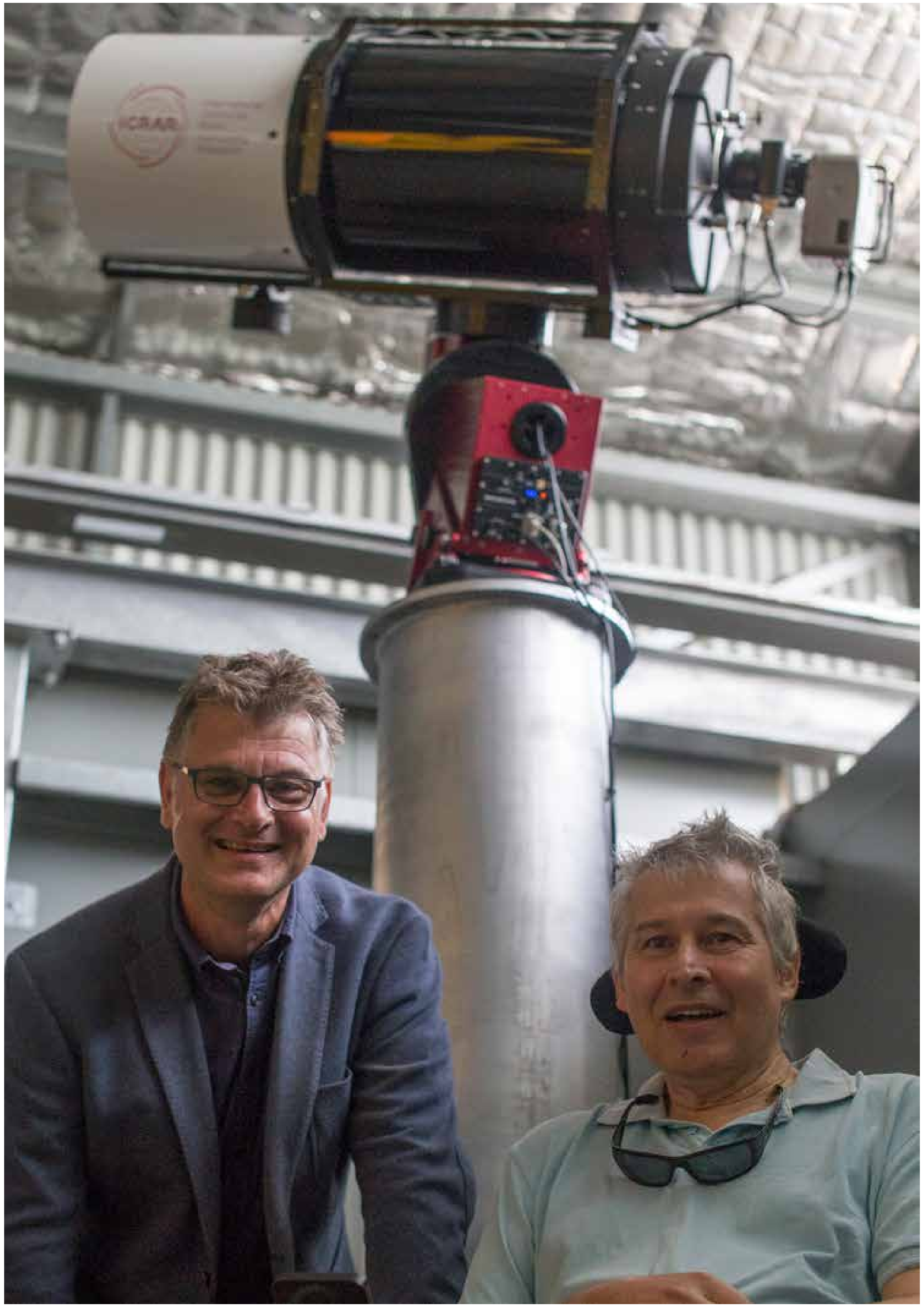
"This is students doing genuine science."

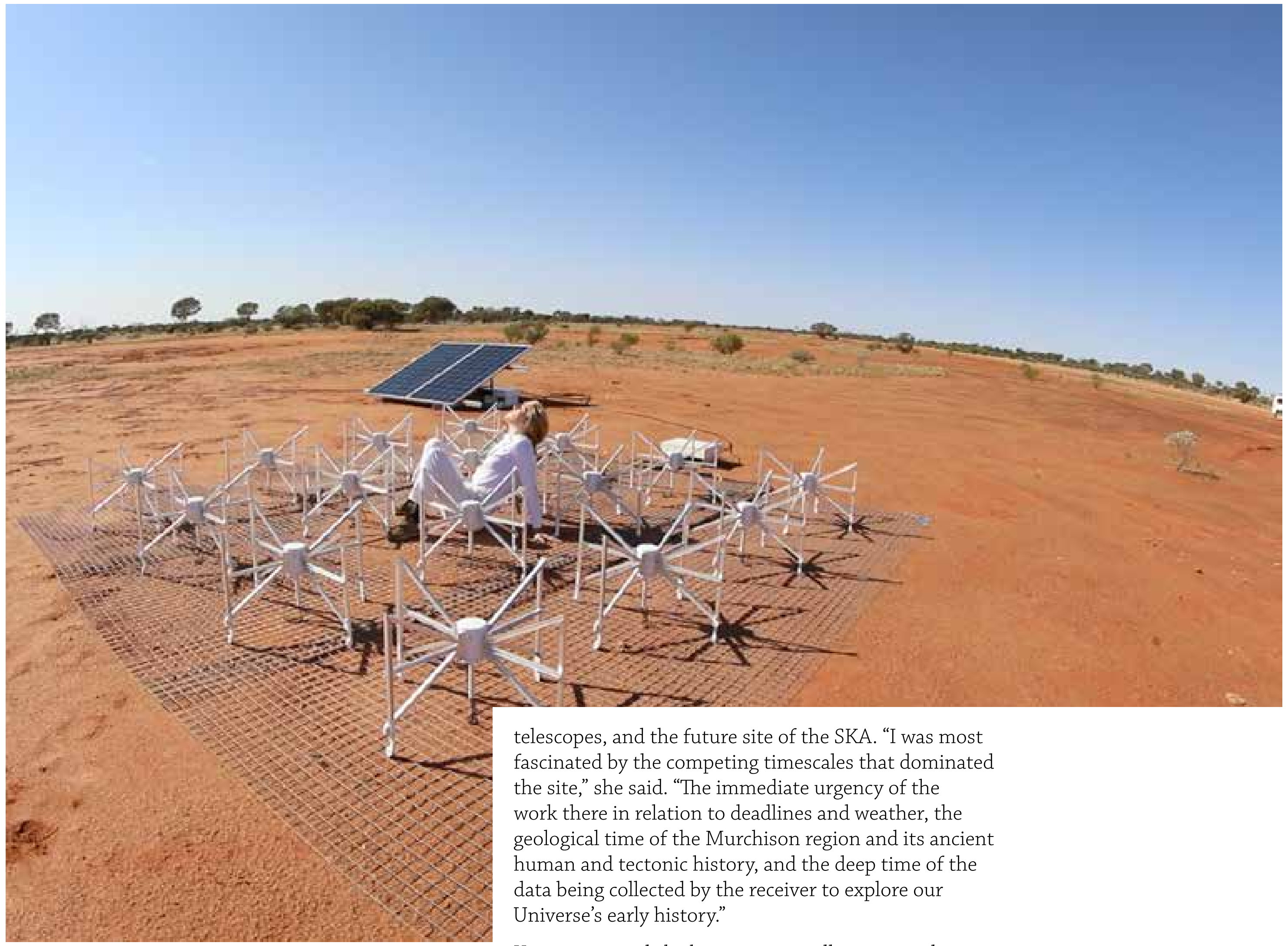
SPIRIT 3, which was donated by Neil Shaw and his wife Tara, is a 35cm Schmidt-Cassegrain telescope.

It has a 20 arc minute square field-of-view and was launched in April 2018.

SPIRIT 4, which was donated by Colin Eldridge, was launched in July 2018.

The 32cm Corrected Dall-Kirkham telescope offers a 50 arc minute field-of-view, the SPIRIT initiative's largest and perfect for wide-field imaging.





Artist-in-residence Loren Kronemyer on site at the Murchison Radio-astronomy Observatory.

Dalkeith Primary Students creating constellation stargazers.

ICRAR hosts inaugural artist-in-residence

ICRAR's first artist-in-residence visited the Murchison Radio-astronomy Observatory, developed a public exhibition and worked with primary school students to send messages into space.

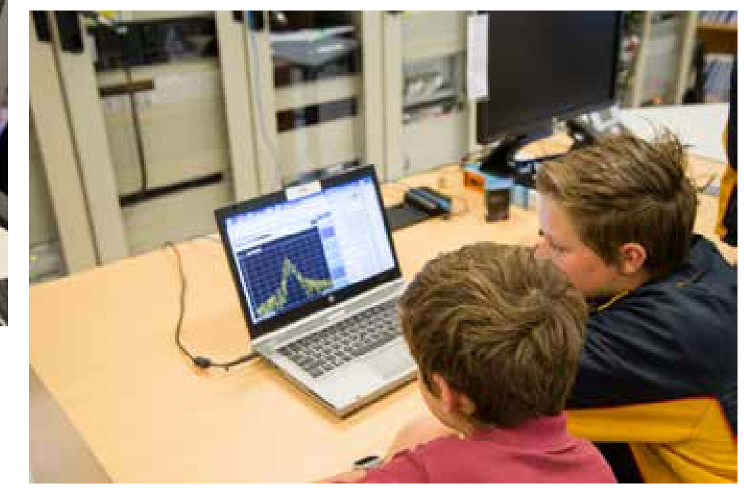
Leonardo da Vinci believed that to develop a complete mind you must study the science of art and the art of science. "Learn how to see," he reportedly said. "Realise that everything connects to everything else."

In 2016, ICRAR appointed the Centre's first artist-in-residence, Californian artist Loren Kronemyer. From the moment she arrived, Kronemyer immersed herself in life at ICRAR. She attended Astro Morning Teas and seminars, explored ICRAR's research archive, and interviewed several researchers and other staff.

In October 2017, Kronemyer spent a week embedded with ICRAR's team at the Murchison Radio-astronomy Observatory (MRO), home of the ASKAP and MWA telescopes, and the future site of the SKA. "I was most fascinated by the competing timescales that dominated the site," she said. "The immediate urgency of the work there in relation to deadlines and weather, the geological time of the Murchison region and its ancient human and tectonic history, and the deep time of the data being collected by the receiver to explore our Universe's early history."

Kronemyer said she became especially interested in the types of expression used by researchers to discuss concepts that far exceed our common understanding of scale. "I compiled notebooks documenting the analogies, metaphors, and anecdotes scientists used to discuss their work, and collected visual and textual representations through interviews and publications," she said.

"Of the topics I learned about, the one that most impacted me most was the research surrounding the Epoch of Reionisation. Learning about this has radically shifted the time-scale I use to think through my work, and I have explored my connection to this research through multiple artistic experiments, including texts, drawing, video, and performance."



Amelie Parsons counting down "3, 2, 1, mark" and releasing her signal to Proxima Centauri. In less than 20 hours the signal will have overtaken the Voyager probe, launched in 1977!

Current and ex Dalkeith Primary School students with the European Space Agency 35m tracking dish in New Norcia. The dish has just started tracking Proxima Centauri in preparation to send the students' message to our nearest stellar neighbour.

Watching the transmission of one of the students' signals to Proxima Centauri.

In October and November 2018, Kronemyer presented a public showcase of artwork titled Receiver at ICRAR-UWA. This show, presented with support from SymbioticA and included in the Unhallowed Arts program, included a large photographic collage of images from the MRO displayed as a floor installation. The show also displayed drawings made by imprinting the receiver's electronic circuitry into paper with carbon.

Kronemyer also worked with ICRAR senior research fellow Kevin Vinsen on a project that saw Dalkeith Primary School students devise messages to send to space. Kronemyer proposed that the students create their own 'golden record' to transmit into the cosmos, based on the Voyager records. Over several weeks of workshops, each student created a suite of images and sounds that were edited into a package. This was then broadcast into space by the European Space Agency from their deep space antenna at New Norcia.

6

AWARDS

And the winner is...

ICRAR would like to congratulate the following researchers and postgraduate students for award-winning excellence in 2017 and 2018.

Dr Luca Cortese
Bappu Gold Award (2017)

David Gozzard
ExxonMobil Student Scientist of the Year, WA Science Awards (2017)

Dr Natasha Hurley-Walker
WA Young Tall Poppy Scientist of the Year (2017)

Chenoa Tremblay
Ken and Julie Michael Prize (2017)

Tristan Reynolds
Ken and Julie Michael Prize (2017)

Ryan Bunney
Westpac Future Leaders Scholarship (2018)

Dr Natasha Hurley-Walker
ABC's Top 5 Scientists for 2018

Ryan Urqhart
ExxonMobil Student Scientist of the Year, WA Science Awards (2018)

Dr Luke Davies
WA Young Tall Poppy Science Award (2018)

Ahmed Elagali
Ken and Julie Michael Prize (2018)

Sam McSweeney
Ken and Julie Michael Prize (2018)

Dr Barbara Catinella
Anne Green Prize, Astronomical Society of Australia (2018)

Dr Natasha Hurley-Walker
Superstar of STEM for 2019/2020

7

STAFF & STUDENTS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1

Kamran Ali, ICRAR-UWA
PhD Candidate, January '15
Information Content of Cosmic Structure.

2

Fatimah Alosaimi, ICRAR-UWA
Student - Masters, July '17

3

Gemma Anderson, ICRAR-Curtin
Discovery Early Career Researcher, September '15
Rapid-response radio follow-up of high-energy transients, including: accreting sources, gamma-ray bursts, supernovae and flare stars.

4

Stephen Andrews, ICRAR-UWA
PhD Graduate, February '14 - October '17
Measuring and Modelling the Extragalactic Background Light using the GAMA survey.

5

Wayne Arcus, ICRAR-Curtin
PhD Candidate, June '16
Fast Radio Bursts as Cosmic Probes.

6

Benjamin Armstrong, ICRAR-UWA
Student - Masters, February '17 - July '18
Formation of the oldest star clusters from fractal massive molecular clouds.

7

Pikky Atri, ICRAR-Curtin
PhD Candidate, April '17
Black hole natal kicks: Using space velocities to constrain how black holes form.

8

Fiona Audcent-Ross, ICRAR-UWA
PhD Candidate, April '13
Star Formation in the Local Universe.

9

Rene Baelemans, ICRAR-Curtin
PhD Candidate, June '17
Co-Design of wideband polarisation-agile phased-array antennas and low-noise amplifiers for the next generation radio telescopes.

10

Arash Bahramian, ICRAR-Curtin
Research Associate, April '18
Multi-wavelenght study of X-ray binaries, Accretion physics, and globular clusters.

11

Lucie Bakels, ICRAR-UWA
PhD Candidate, March '17
Improved models for stellar feedback in dwarf galaxies.

12

Robert Bassett, ICRAR-UWA
Research Associate, February '16 - February '17
Galaxy formation and evolution; Gas accretion; N-body simulations versus observations.


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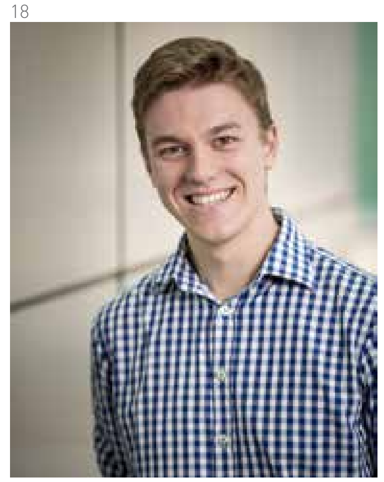
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13

Kenji Bekki, ICRAR-UWA
Principal Research Fellow, January '10
Application of artificial intelligence to astronomy; Formation of star clusters and galaxies; Origins of the Magellanic system; Cosmic dust.

14

Sabine Bellstedt, ICRAR-UWA
Research Associate, October '18
Galaxy evolution; Large galaxy surveys; Galaxy kinematics.

15

Ramesh Bhat, ICRAR-Curtin
Senior Research Fellow, June '12
Observational pulsar astronomy including pulsar scintillation; Surveys for pulsars and fast radio bursts and their follow ups; Pulsar timing arrays for the detection of gravitational waves; Binary-pulsar timing, astrometry and the theories of gravity.

16

Julian Bocking, ICRAR-UWA
Student - Masters, July '17
Design of the SKA1-Mid Phase-stabilisation System Transmitter Module.

17

Tom Booler, ICRAR-Curtin
Director, Operations, February '11
Program management.

18

Mark Boulton, ICRAR-UWA
Senior Systems Engineering/IT Manager, March '12
Server/Infrastructure design/maintenance/support; Systems Engineering; Software design and coding.

19

Matías Andrés Bravo Santa Cruz, ICRAR-UWA
PhD Candidate, March '18
The DEVILS Galaxy Group Catalogue: The environmental effect on galaxies and its evolution at intermediate redshift.

20

James Buchan, ICRAR-Curtin
PhD Candidate, March '15
Photovoltaic-Battery Power Systems for the SKA Radio Telescope Considering Electromagnetic Compatibility Characterisation.

21

Ryan Bunney, ICRAR-UWA
PhD Candidate, June '18
Multi-workflow Target-of-Opportunity Scheduling for the SKA Science Data Processor.

22

Andrew Butler, ICRAR-UWA
PhD Candidate, January '15
Measuring AGN Feedback: Black Hole Kinetic Luminosity Outputs from High and Low Excitation Radio Galaxies.

23

Rodrigo Canas Vazquez, ICRAR-UWA
PhD Candidate, May '16
Understanding the Galaxy-AGN connection and its evolution through cosmic time using numerical simulations.

24

Barbara Catinella, ICRAR-UWA
ARC Future Fellow/Senior Research Fellow, September '15
Extragalactic HI surveys; Environmental effects on galaxy evolution; Galaxy scaling relations.

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25

Mitchell Cavanagh, ICRAR-UWA
Student - Masters, February '18
Exploring Galaxy Evolution with Deep Learning.

26

Garima Chauhan, ICRAR-UWA
PhD Candidate, September '17
Modelling Neutral Hydrogen Lines in Semi-Analytical Models.

27

Jaiverdhan Chauhan, ICRAR-Curtin
PhD Candidate, February '18
Using SKA precursors to understand the properties of X-ray binary jets.

28

Qingxiang Chen, ICRAR-UWA
PhD Candidate, October '15
Neutral hydrogen via spectral stacking.

29

Rajan Chhetri, ICRAR-Curtin
Research Associate, April '16
Active galactic nuclei; Compact sources at low radio frequencies using widefield interplanetary scintillation; Multi-wavelength study of radio populations; Radio interferometry techniques.

30

Evelyn Clune, ICRAR-Curtin
Administrative Officer, October '15 - June '18
Administration.

31

Robin Cook, ICRAR-UWA
PhD Candidate, March '17
The Connection Between Structure and Cold Gas Reservoirs in Galaxies.

32

Ian Cooper, ICRAR-UWA
Project Manager, March '13 - February '17
SKA Science Data Processor Project Management.

33

Luca Cortese, ICRAR-UWA
Senior Research Fellow/ARC Future Fellow, September '15
Extragalactic astronomy; Galaxy Evolution; Gas and star formation cycle in galaxies.

34

Brian Crosse, ICRAR-Curtin
Instrument Engineer - Signal Chain, January '11
Low Frequency Radio Astronomy Engineering.

35

Dylan Cusack-Pacquelet, ICRAR-UWA
Student - Masters, February '16 - March '18
Developing the StarFox Telescope for Deep Sky Imaging.

36

Jacqueline Da Gama, ICRAR-UWA
Finance Manager, August '15
Responsible for all financial matters relating to all ICRAR grants; Providing finance related advice to Centre staff in the matters of accounting, budgeting, and management reporting; Ensuring compliance with all financial and accounts requirements.


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Brenda Dagnall, ICRAR-UWA
Executive Assistant, June '16 - March '17
Executive Assistance to Professor Peter Quinn; Administration.

38

David Davidson, ICRAR-Curtin
Director, Engineering, January '18
Radio astronomy engineering; antenna design, simulation and metrology; computational electromagnetics.

39

Luke Davies, ICRAR-UWA
WAVES Project Scientist, October '13
Galaxy evolution; Muliwavelength surveys; Star formation; Galaxy interactions.

40

Foivos Diakogiannis, ICRAR-UWA
Research Associate, July '14 - June '17
Theoretical and computational Galactic Dynamics; Galactic archaeology; Mass modelling; Evolutionary Algorithms.

41

Jonathan Diaz, ICRAR-UWA
Research Associate, March '17
Galaxy evolution and transformation using N-body simulations.

42

Benjamin Dix-Matthews, ICRAR-UWA
PhD Candidate, August '18
Coherent optical free-space time and frequency dissemination.

43

Richard Dodson, ICRAR-UWA
Senior Research Fellow, September '09
Data Intensive and Astronomical Methods for the SKA; Calibration of interferometers at low and high frequencies; Time domain astronomy with interferometers.

44

Markus Dolensky, ICRAR-UWA
Technical Leader, January '14
Technical project management; Scientific data processing systems.

45

Simon Driver, ICRAR-UWA
Winthrop Research Professor, April '11
Evolution of mass; Evolution of energy; Evolution of structure.

46

Guillaume Drouart, ICRAR-Curtin
Research Associate, November '15
Black hole and galaxy evolution at the edge of the Universe.

47

Stefan Duchesne, ICRAR-Curtin
PhD Candidate, February '18
A census of radio halos and relics with the MWA.

48

Geoff Duniam, ICRAR-UWA
PhD Candidate, March '14
Big Data in Radio Astronomy.


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Angela Dunleavy, ICRAR-Curtin
Administrative Coordinator, June '12
Administration.

50

Wiebke Ebeling, ICRAR-Curtin
CAASTRO Education and Outreach Manager, July '11 - Dec '17
Science Communication: science news stories, media releases; Science Education: video productions, hands-on tools; Science Outreach: displays, visualisations, publications.

51

Ahmed Elagali, ICRAR-UWA
PhD Candidate, May '16
Studies of Interacting Galaxies & the Environmental Effects on Their Evolution.

52

Pascal Elahi, ICRAR-UWA
Research Fellow (ASTRO 3D), April '16
Numerical Astrophysics; Galaxy Formation; Cosmology.

53

David Emrich, ICRAR-Curtin
Radio Astronomy Instrumentation Engineer, September '09
Radio Astronomy Engineering.

54

Lisa Evans, ICRAR-UWA
Citizen Science Project Officer, October '17
Helping to design and project manage the ICRAR citizen science project, AstroQuest; testing and evaluating the communication and outreach outcomes of citizen science for ICRAR.

55

Bi-Qing For, ICRAR-UWA
Research Fellow (ASTRO 3D), August '11
Stellar evolution; HI surveys; Galaxy evolution and formation; Multiwavelength studies of the Magellanic System.

56

Sam Foster, ICRAR-UWA
Project Officer, November '14
Data Intensive Machine Learning.

57

Patrick Francis, ICRAR-UWA
Student - Masters, July '18
Very Long Baseline Optical Intergerometry.

58

Thomas Franzen, ICRAR-Curtin
Postdoctoral Researcher, April '14 - July '17
Extragalactic continuum radio surveys; Population and evolutionary studies of radio galaxies.

59

Jonah Gannon, ICRAR-UWA
Student - Masters, July '16 - March '18
Developing the StarFox Telescope for Deep Sky Imaging.

60

Lilian Garratt-Smithson, ICRAR-UWA
Research Associate, July '18
Galaxy Evolution; Stellar Feedback; Computational Astrophysics; Investigating the atomic Hydrogen content of galaxies; Linking simulations to the ASKAP-FLASH survey.


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Morgan Goodman, ICRAR-Curtin
Student - Masters, August '16 - July '18
Formation and evolution of dwarf galaxies with different types.

62

Kirsten Gottschalk, ICRAR-UWA
Astronomy Ambassador, January '10
Online communication and social media; Media liaison; Science Writing; Graphic and web design; Event Management; Work Experience and Studentship Student Support; Resources and events for schools.

63

David Gozzard, ICRAR-UWA
PhD Candidate and Research Associate, February '14 - April '18
Stabilised transfer of time and frequency for space science applications.

64

Guido Granda, ICRAR-UWA
PhD Candidate, May '16 - March '17
Synthetic Universes of the Radio Sky.

65

Charles Gravestock, ICRAR-UWA
Masters Graduate, Engineer, July '17
Testing the SKA1-mid synchronisation system on overhead optical fibre with the MeerKAT telescope.

66

Kexin Guo, ICRAR-UWA
Visiting Research Fellow, October '17
Galaxy formation and evolution.

67

Peter Hall, ICRAR-Curtin
Director, Engineering/Professor Emeritus, September '09 - August '17
Radio astronomy engineering; SKA design and verification; Engineering education.

68

Paul Hancock, ICRAR-Curtin
Early Career Research Fellow, September '13
Low frequency radio variability; Fireballs and meteors; Software and methods to support astronomy.

69

Kate Harborne, ICRAR-UWA
PhD Candidate, October '16
Using numerical simulations to investigate observable galaxy kinematics.

70

Jennifer Hardwick, ICRAR-UWA
Student - Masters, February '18

71

Hosein Hashemizadeh, ICRAR-UWA
PhD Candidate, January '17
The emergence of bulges and disks.

72

Gregory Hellbourg, ICRAR-Curtin
Senior Research Fellow, November'18
Signal processing; Radio Frequency Interference mitigation; SETI; Instrumentation.


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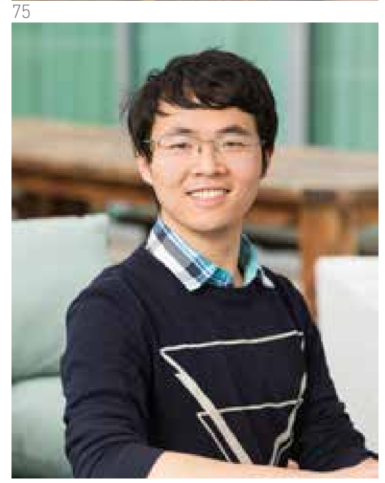
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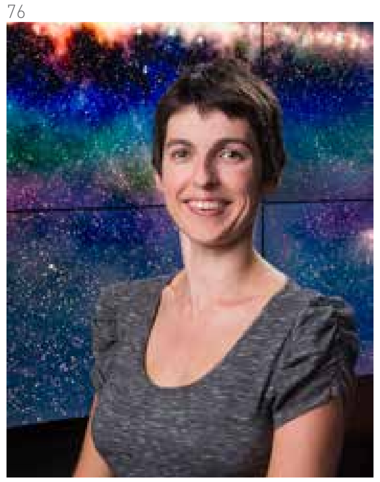
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73

Brendan Hennessy, ICRAR-Curtin
PhD Candidate, March '18
Surveillance of Space with Passive Radar using the Murchison Widefield Array.

74

Torrance Hodgson, ICRAR-Curtin
PhD Candidate, May '18
Searching for the Synchrotron-Emitting Cosmic Web.

75

Luke Horsley, ICRAR-Curtin
Engineering Support Technician, August '15 - May '18
Fieldwork logistics and engineering support.

76

Joshua Horton, ICRAR-UWA
Student - Masters, July '17
Towards the Direct Imaging of Expoplanets.

77

Cullan Howlett, ICRAR-UWA
Research Associate (CAASTRO), October '15
Large galaxy surveys; Cosmology; Large scale structure.

78

Wenkai Hu, ICRAR-UWA
Visiting PhD Candidate, June '17 - June '18
The Cosmic Gas Density and the Environmental Dependence of Galaxy Evolution.

79

Natasha Hurley-Walker, ICRAR-Curtin
Senior Research Fellow, August '11
Radio astronomy; Astronomical surveys; Supernova remnants; Galaxy clusters; Radio galaxies.

80

Minh Huynh, ICRAR-UWA
Senior Data Scientist (CSIRO)/Adjunct Research Fellow (UWA), September '10
Galaxy evolution; Active galactic nuclei; Radio surveys.

81

Carole Jackson, ICRAR-Curtin
Director, Science (Curtin), August '13 - March '17
Extragalactic radio source evolution; Technologies for radio astronomy; Industry engagement strategies & large projects.

82

Clancy James, ICRAR-Curtin
Research Fellow, July '17
Fast radio bursts with CRAFT and ASKAP; Cosmic ray detection with the MWA, FASTand the SKA; neutrino astronomy with ANTARES and KM3NeT.

83

Steven Janowiecki, ICRAR-UWA
Postdoctoral Research Fellow, September '15 - June '18
Galaxy Evolution and Star Formation; Optical and Radio Observations.

84

Rabah Abdul-Jabbar Jasem, ICRAR-Curtin
PhD Candidate, April '14
High Resolution Direction of Arrival Estimation using Switched Parasitic Antenna Arrays with Switched Active Elements.


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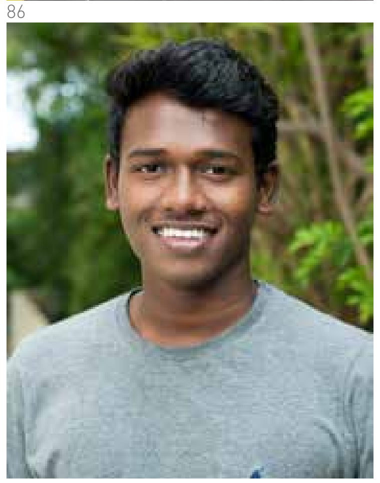
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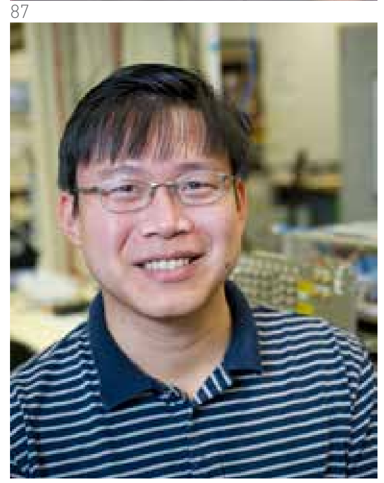
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85

Emily Johnson, ICRAR-Curtin
Administrative Officer, July '18
Administration.

86

Melanie Johnston-Hollitt, ICRAR-Curtin
Research Professor, January '18
Galaxy clusters and the cosmic web; Cosmic magnetism; Imaging algorithms.

87

Christopher Jordan, ICRAR-Curtin
Research Associate, October '15
Epoch of Reionisation; Ionospheric science; High mass star formation.

88

Ronniy Joseph, ICRAR-Curtin
PhD Candidate, October '16
Probing the Epoch of Reionization with Non-Traditional Hybrid Arrays.

89

Bhan Prince Raj Joseph Sivaraj, ICRAR-UWA
Student - Masters, February '18

90

Budi Juswardy (Alex Wu), ICRAR-Curtin
Research Engineer, January '11
Radio Frequency Systems; Electronic Circuit Design; Fibre Optic Communications, Reliability and Risk Assessment; Power Systems.

91

Prajwal Kafle, ICRAR-UWA
Research Associate, May '14 - March '18
Formation and evolution of galaxies, in particular Milky Way-like galaxies.

92

Leah Kalimeris, ICRAR-UWA
Student - Masters, February '17 - November '18
HII edges in galactic disks in HI selected galaxies.

93

Anna Kapinska, ICRAR-UWA
Research Associate (CAASTRO), August '13 - March '18
Radio galaxies; Relativistic jets; AGN feedback; Radio continuum surveys.

94

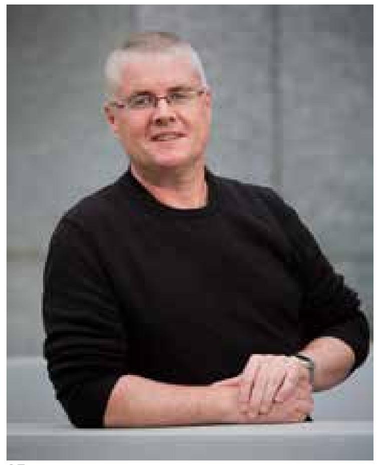
Dilpreet Kaur, ICRAR-Curtin
PhD Candidate, June '17
Tracking interstellar space weather toward timing-array millisecond pulsars.

95

Adela Kawka, ICRAR-Curtin
Senior Research Fellow, March '18
White dwarf stars; late stellar evolution;
Galactic archaeology; optical spectroscopy; and spectropolarimetry.

96

Katharine Kelley, ICRAR-UWA
PhD Candidate, June '14
A Radio Astronomy Search for Axion Dark Matter.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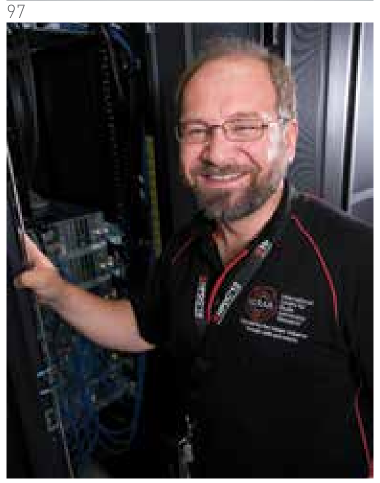
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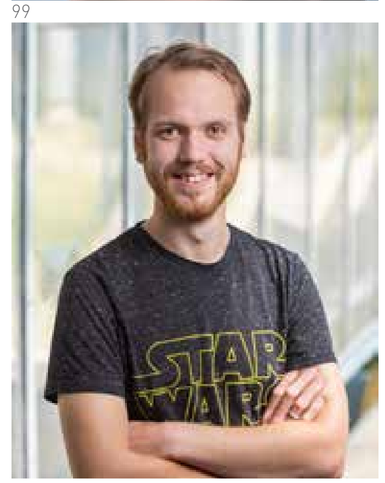
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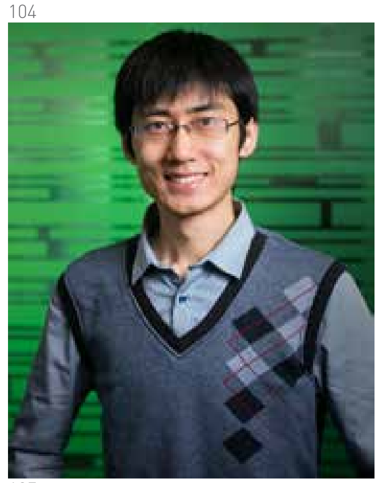
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97

David Kenney, ICRAR-Curtin
Senior Technical Officer, April '14
Support the ICRAR radio astronomy engineering laboratory; Leading role in the development, deployment and validation of SKA pre-construction systems; Design, prototype and test radio astronomy instrumentation; Support engineering projects undertaken by staff and students.

98

Do Won Kim, ICRAR-Curtin
PhD Candidate, March '16
Improved Design of Wireless Electrical Energy Transfer System for Various Power Applications.

99

Franz Kirsten, ICRAR-Curtin
Research Associate, October '14 - September '17
Pulsar scintillometry; Pulsar astrometry; Astrometry of compact object; Radio interferometry.

100

Slava Kitaeff, ICRAR-UWA
Australian SKA Regional Centre Project Lead, May '11
Big data; Algorithms; Software; Universe(s).

101

Soheil Koushan, ICRAR-UWA
PhD Candidate, March '16
Measuring the Cosmic Optical Background Light using the WAVES Input Catalogue.

102

Mike Kriele, ICRAR-Curtin
PhD Candidate, March '18
High Precision Mapping of the Diffused Low Frequency Sky.

103

Claudia Lagos, ICRAR-UWA
Senior Research Fellow, May '15
Galaxy formation in cosmological simulations.

104

Jie Li, ICRAR-UWA
Student - Masters, July '17
Kinematic and environmental regulation of atomic gas in galaxies.

105

Lincheng Li, ICRAR-UWA
PhD Candidate, November '16
Intensity Mapping, a New Technique to Study the Evolution of the Universe.

106

Jack Line, ICRAR-Curtin
Research Associate, August '18
Epoch of reionisation; Simulating interferometric observations; Building calibration models.

107

Boyang Liu, ICRAR-UWA
PhD Candidate, February '16
Early ASKAP Science: Cold Atomic Gas and Molecular Hydrogen Formation in the Magellanic Clouds.

108

Paul Luckas, ICRAR-UWA
SPIRIT Program Manager, March '16
Robotic telescopes in Education.


109

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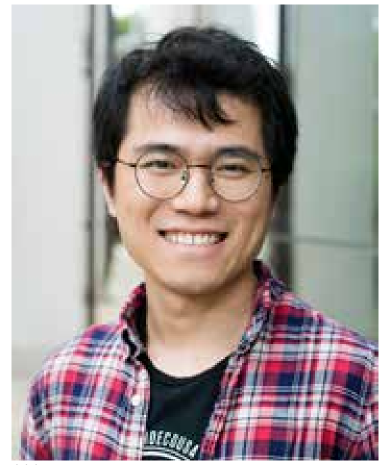
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109

Aaron Ludlow, ICRAR-UWA
Future Fellow, June '17
Probing Dark Matter Through the Small Scale Structure of the Universe.

110

Christene Lynch, ICRAR-Curtin
Research Associate, July '18
Epoch of Reionisation; Polarised transients; Stellar radio emission.

111

Xuanyi Lyu, ICRAR-UWA
Student - Masters, February '18

112

Damien Macpherson, ICRAR-UWA
PhD Graduate, February '12 - January '17
Optimal strategies for detecting the first stars: the biggest explosions in the Universe.

113

Jean-Pierre Macquart, ICRAR-Curtin
Senior Research Fellow, September '09
Fast Radio Bursts; Scintillation and Wave Propagation Theory; The Interstellar and Intergalactic Medium; Pulsars; The Galactic Centre.

114

JT Malarecki, ICRAR-UWA
PhD Candidate, March '15
Organisation and exploration of very large imagery data in the SKA.

115

Jurek Malarecki, ICRAR-UWA
PhD Graduate, January '11
The Warm-Hot Intergalactic Medium.

116

Yolandie McDade, ICRAR-UWA
Executive Assistant, May '11
Executive Assistance to Professor Peter Quinn; Administration.

117

Ben McKinley, ICRAR-Curtin
Research Fellow, July '17
Epoch of reionisation science, in particular detecting the sky-averaged signal from neutral hydrogen using interferometers (and the Moon!); Radio galaxies; Calibration and imaging of low-frequency radio interferometric data.

118

Andrew McPhail, ICRAR-Curtin
MRO ICRAR Site Safety Officer, August '18
MRO Site Co-ordinator responsible for equipment and personnel logistics, to, from and within site.

119

Sam McSweeney, ICRAR-Curtin
PhD Candidate, March '16
Investigating Emission Mechanisms by Mapping Pulsar Magnetospheres in Three Dimensions.

120

Michael Messineo, ICRAR-UWA
Student - Masters, July '17 - July '18
Coherent free-space laser links for space applications.


121


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121

Gerhardt Meurer, ICRAR-UWA
Winthrop Research Professor, January '10
Galaxies: formation and evolution.

122

Martin Meyer, ICRAR-UWA
Senior Research Fellow, September '09
HI surveys; Galaxy formation and evolution.

123

Scott Meyer, ICRAR-UWA
PhD Candidate, February '12
Investigating the Tully-Fisher relation and galaxy kinematics through neutral Hydrogen spectral line stacking techniques.

124

Bradley Meyers, ICRAR-Curtin
PhD Candidate, February '16
Investigating the Links between Radio Pulsar Populations that display Intermittent Emission Phenomena at Low Frequencies.

125

James Miller-Jones, ICRAR-Curtin
Director, Science (Curtin), July '10
X-ray binaries; Jets; Accretion physics; Radio transients.

126

Seema Morab, ICRAR-Curtin
PhD Candidate, January '18
Emission Mechanisms and Energetics of Fast Radio Bursts.

127

John Morgan, ICRAR-Curtin
Research Fellow, May '10
Extra-galactic science with the MWA; Solar science with the MWA; VLBI and interferometry; Education and outreach.

128

Ian Morrison, ICRAR-Curtin
Research Fellow, July '18
Radio astronomy signal processing; the Search for Extraterrestrial Intelligence (SETI).

129

Steven Murray, ICRAR-Curtin
Research Associate/PhD Graduate, April '12 - September '18
Epoch of Reionisation; Large Scale Structure; Astrostatistics.

130

Ainulnabilah (Bella) Nasirudin, ICRAR-Curtin
PhD Candidate, June '17
Discriminating Epoch of Reionisation (EoR) Source Models with Low-Frequency Radio Interferometers.

131

Bach Nguyen, ICRAR-Curtin
PhD Candidate, March '17
Removal of Radio-frequency Interference from Terrestrial Broadcast Stations in the Murchison Widefield Array.

132

Tracey O'Keefe, ICRAR-UWA
Administrative Officer, April '14
Administration; HR; General Finance.


133


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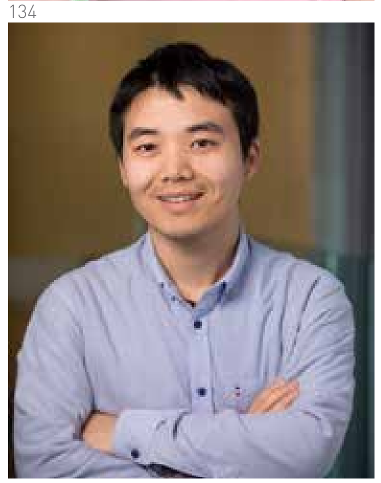
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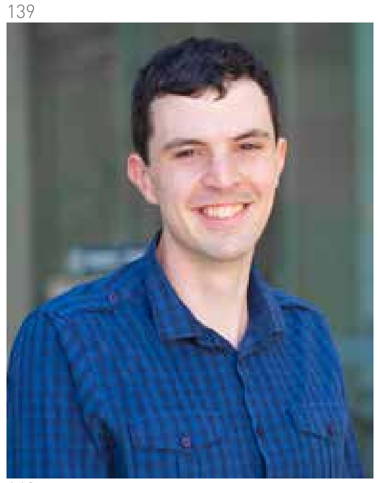
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133

Danail Obreschkow, ICRAR-UWA
Senior Research Fellow, October '11
Galaxy evolution theory; Cosmology; Hydrodynamics.

134

Vitaliy Ogarko, ICRAR-UWA
Research Associate, November '17
Radio astronomy calibration algorithms for the scale of the SKA; Numerical methods for high performance computing; Scientific software engineering.

135

Omima Osman, ICRAR-UWA
PhD Candidate, January '18
Dust formation and evolution, and its influence on galaxy evolution.

136

Dave Pallot, ICRAR-UWA
Software Engineer and Administrator, January '15
Software Engineering; Survey Science Support Engineering; IT Administration.

137

Hengxing Pan, ICRAR-UWA
Visiting PhD Candidate, December '16 - January '18
Analysing large-scale galaxy bias.

138

Nipanjana Patra, ICRAR-Curtin
Research Fellow, October '18
Precision observational cosmology; evolutionary history of the Universe.

139

Clare Peter, ICRAR-UWA
Administration Officer (ASTRO 3D), August '13
ASTRO3D Administration and Finance.

140

Richard Plotkin, ICRAR-Curtin
Senior Research Fellow - Peter Curran Memorial Fellow, November '15
Black Hole Accretion; Relativistic Jets; Multiwavelength Observations.

141

Attila Popping, ICRAR-UWA
Research Fellow (CAASTRO), November '10
Galaxy Evolution; Neutral Hydrogen Surveys; Neutral Hydrogen in the Intergalactic Medium.

142

Rhys Poulton, ICRAR-UWA
PhD Candidate, September '16
Studying the orbits and interactions of satellite galaxies in the next generation of surveys and simulations.

143

Chris Power, ICRAR-UWA
Research Professor & ARC Future Fellow, March '11
Galaxy Formation and Evolution; Dark Matter; Scientific High Performance Computing.

144

Melinda Powers, ICRAR-UWA
Student - Masters, February '17
Recovering cosmic star-formation histories from stacked photometry and spectra of nearby galaxies.


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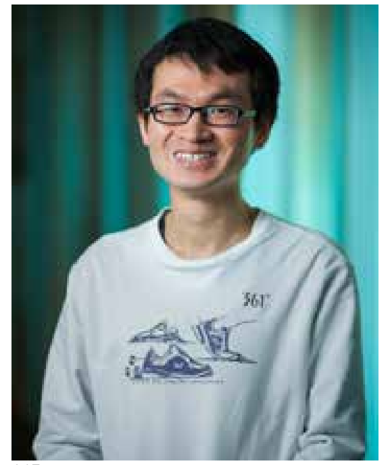
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145

Steve Raj Prabu, ICRAR-Curtin
Student - Masters, August '18
Using MWA as a receiver for a passive radar system aimed at detecting and characterising space debris.

146

Hai-Hua Qiao, ICRAR-Curtin
PhD Graduate, October '14 - May '18
Accurate OH maser positions from SPLASH: Understanding the origins of OH masers with an unbiased survey.

147

Fei Qin, ICRAR-UWA
PhD Candidate, November '15
Bulk flow and peculiar velocity.

148

Louisa Quartermaine, ICRAR-UWA
Project Manager, January '17
Provide project management support to the Data Intensive Astronomy Team including performing the role of Deputy SKA-SDP Project Manager.

149

Peter Quinn, ICRAR-UWA
Executive Director, September '09
Galaxy formation and evolution; Dark matter; Computational cosmology and data intensive astronomy.

150

Lisa Randell, ICRAR-UWA
Administrative Assistant, July '14
Administration; Reception; Purchasing; Visitor Travel/ Accommodation.

151

Tristan Reynolds, ICRAR-UWA
PhD Candidate, February '17
Neutral hydrogen observations of the local universe.

152

Jonghwan Rhee, ICRAR-UWA
Research Fellow (ASTRO 3D), June '14
HI surveys; 21-cm cosmology.

153

Maria Rioja, ICRAR-UWA
Senior Research Fellow (ICRAR-CSIRO), September '09
Interferometric observations, imaging, and high precision astrometry; Development of innovative Calibration techniques for next-generation telescopes; Studies of AGNs, star forming regions, evolved stars; SKA.

154

Aaron Robotham, ICRAR-UWA
Senior Research Fellow, January '13
Galaxy Evolution; Dark Matter; Large Scale Structure.

155

Gregory Rowbotham, ICRAR-UWA
Cosmos Consultant, March '16
Outreach, Education and Communication.

156

Cass Rowles, ICRAR-UWA
Cosmic Communicator, October '17
Science communication, social media, videography and website management.


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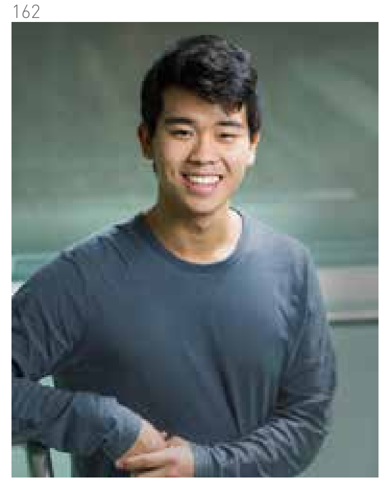
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157

Kristof Rozgonyi, ICRAR-UWA
PhD Candidate, August '17
Optimisation of deep spectral imaging pipelines for next generation radio telescopes.

158

Tina Salisbury, ICRAR-Curtin
Operations Coordinator, January '10
Finance and Administration.

159

Sascha Schediwy, ICRAR-UWA
Research Fellow, February '14
Phase synchronisation of the SKA telescope; Laser timing links for space science applications; Phased array technologies.

160

Franz Schlagenhaufer, ICRAR-Curtin
Research Engineer, March '10 - June '17
Electromagnetic Compatibility; Electromagnetic measurements; Electromagnetic simulations.

161

Nick Seymour, ICRAR-Curtin
Senior Lecturer, July '14
Active Galactic Nuclei; Galaxy Evolution; Multi-wavelength Surveys.

162

Manan Shah, ICRAR-UWA
Student - Masters, February '17
Deep Learning Systems for Astrophysical Simulations.

163

Ryan Shannon, ICRAR-Curtin
Research Fellow, June '15 - October '17
Observations of pulsars; Searches for fast radio bursts; Searches for gravitational waves.

164

Renu Sharma, ICRAR-UWA
Associate Director, Chief Operating Officer, September '09
ICRAR management, planning, execution, compliance, and reporting; Creating and supporting an enabling and inclusive culture at ICRAR; Supporting ICRAR governance and helping plan for the long term sustainable future of ICRAR.

165

Austin Shen, ICRAR-UWA
Student - Masters, March '16 - March '18
Earth's tidal energy resource: from geophysics to astrophysics.

166

Gurashish Singh-Bhatia, ICRAR-UWA
Student - Masters, February '16
The Central Redundant Array Mega-Tile at the Murchison Radio-astronomy Observatory.

167

Teresa Slaven-Blair, ICRAR-Curtin
Outreach Support Coordinator (ASTRO 3D), April '18
Coordinate the outreach efforts of the ASTRO 3D Epoch of Reionisation researchers at Curtin University.

168

Greg Sleap, ICRAR-Curtin
System Administrator, June '16
Data Management; System Administration; Software Engineering.


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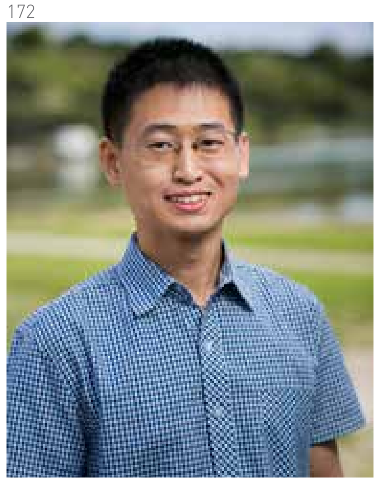
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169

Charlotte Sobey, ICRAR-Curtin
Research Associate, February '16 - August '18
Observing pulsars using Square Kilometre Array precursors and pathfinders to investigate astrophysical magnetic fields.

170

Marcin Sokolowski, ICRAR-Curtin
Research Fellow, January '12
Radio-astronomy instrumentation (Engineering Development Array); Global Epoch of Reionisation experiment (BIGHORNS); MWA staff scientist (observation scheduling, data quality control and ASVO calibration database); MWA beam model; Looking for Fast Radio Bursts with the MWA; Monitoring the RFI environment at the MRO.

171

Roberto Soria, ICRAR-Curtin
Senior Research Fellow, March '11 - July '17
Accretion onto compact objects; X-ray properties of galaxies; Outflows and jets.

172

Lister Staveley-Smith, ICRAR-UWA
Director, Science (UWA), September '09
Radio Astronomy.

173

Adam Stevens, ICRAR-UWA
Research Associate, July '17
Galaxy evolution theory; gas in galaxies; cosmological & hydrodynamic simulations; semi-analytic models; disc angular momentum; mock surveys; galaxy environment.

174

Lucas Storer, ICRAR-UWA
Student - Masters, February '18
Developing the StarFox Telescope for Deep Sky Imaging.

175

Hongquan Su, ICRAR-Curtin
PhD Candidate (submitted), September '14
Mapping the Galaxy in 3D using observations of HII region absorption with the MWA.

176

Adrian Sutinjo, ICRAR-Curtin
Senior Lecturer, January '12
Electromagnetics; Antenna & radio engineering; Radio astronomy instrumentation.

177

Nicholas Swainston, ICRAR-Curtin
PhD Candidate, March '18
Finding pulsars with a next-generation low-frequency radio telescope.

178

Dan Taranu, ICRAR-UWA
Research Associate (CAASTRO), December '14 - January '18
Galaxy evolution; Numerical simulations; Dynamical modelling.

179

Caleb Thomas, ICRAR-UWA
Student - Masters, February '18
Development of an Optical Phased Array to Power Near-Lightspeed Interstellar Travel.

180

Jessica Thorne, ICRAR-UWA
Student - Masters, February '18


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181

Jonathan Tickner, ICRAR-Curtin
Senior Technical Officer, March '10
Electronic engineering; Mechanical fabrication; Logistics; Lab mangement.

182

Steven Tingay, ICRAR-Curtin
Deputy Executive Director, September '09
Development of science, engineering, and computing for the SKA and its precursors, in particular the Murchison Widefield Array.

183

Rodrigo Tobar Carrizo, ICRAR-UWA
Software Engineer, May '15
Software design, development and optimisation; Distributed and control systems; Databases and storage.

184

Chenoa Tremblay, ICRAR-Curtin
PhD Candidate (completed), April '15
A Search for Molecules at Low Frequency with the Murchison Widefield Array.

185

Steven Tremblay, ICRAR-Curtin
Postdoctoral Fellow (CAASTRO), September '11
Fast Radio Transients; Pulsars; Young Radio Galaxies.

186

Cathryn Trott, ICRAR-Curtin
Senior Research Fellow and ARC Future Fellow, February '11
Signal processing theory; Epoch of Reionisation.

187

Vlad Tudor, ICRAR-Curtin
PhD Candidate (submitted), January '15
Quiescent stellar-mass black holes in globular clusters.

188

Ryan Turner, ICRAR-UWA
Student - Masters, February '17 - July '18
The evolution of galaxy structures over time and the fitting of clump galaxies.

189

Daniel Ung, ICRAR-Curtin
Support Engineer, Aperture Array, January '15
Electromagnetic simulation of aperture arrays; Receiver noise calculation; Noise parameter extraction; Radiation efficiency calculation.

190

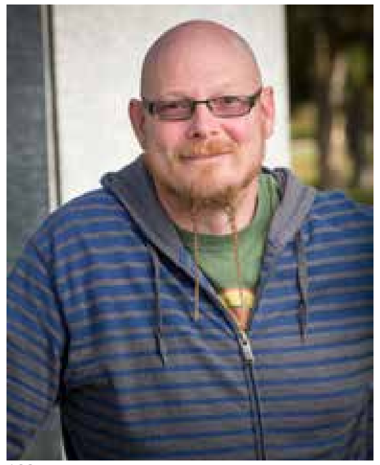
Ryan Urquhart, ICRAR-Curtin
PhD Candidate (submitted), February '15
Exploring regimes of super-Eddington accretion in black hole binaries.

191

Kevin Vinsen, ICRAR-UWA
Senior Research Fellow, July '10
Data Intensity Astronomy; Galaxy Morphology; Machine Learning.

192

Mia Walker, ICRAR-Curtin
Project Officer, February '16
Reporting; Outreach and education.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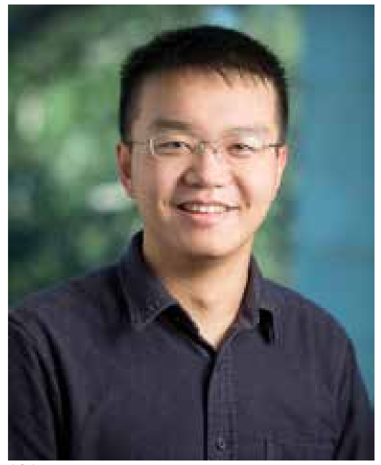
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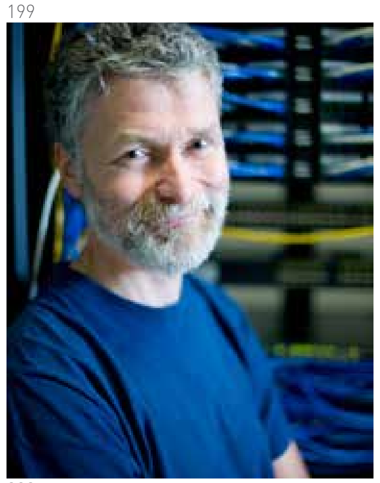
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193

Andrew Walsh, ICRAR-Curtin
Senior Research Fellow, January '13 - January '17
Masers; Star formation; Galactic surveys.

194

Liang Wang, ICRAR-UWA
Research Associate, September '16
Galaxy formation simulation.

195

Adam Watts, ICRAR-UWA
PhD Candidate, March '16
Constraining gas kinematics and distributions with spatially unresolved HI observations.

196

Randall Wayth, ICRAR-Curtin
Research Associate Professor, September '09
Low frequency radio astronomy; Radio astronomy engineering; Epoch of Reionisation science.

197

Toby Weel, ICRAR-UWA
Student - Masters, July '17
Synchronisation of the SKA Radio Telescope.

198

Charlotte Welker, ICRAR-UWA
Jim Buckee Fellow in Astrophysics, November '15 - November '18
Galaxy evolution, large scale-structures, and hydrodynamic simulations.

199

Tobias Westmeier, ICRAR-UWA
Senior Research Fellow, October '10
High-velocity clouds around the Milky Way and nearby galaxies; The Magellanic Stream; Evolution and interaction of galaxies in different environments; Detection and parametisation of galaxies in HI; Large HI surveys with SKA precursors.

200

Pete Wheeler, ICRAR-UWA
Outreach, Education and Communications Manager, September '09
Outreach, Education & Communications.

201

Sarah White, ICRAR-Curtin
Research Associate, October '15 - September '18
Using multi-wavelength surveys to study galaxy evolution; Investigating the radio emission from active galactic nuclei.

202

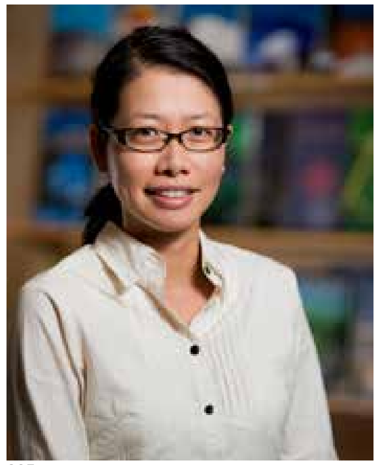
Andreas Wicenec, ICRAR-UWA
Director, Data Intensive Astronomy, August '10
Data Intensive Astronomy; Stellar Astrophysics and Astrometry.

203

Andrew Williams, ICRAR-Curtin
Monitor and Control Engineer, June '13
Instrumentation control; Software and computing.

204

Alexander Williamson, ICRAR-Curtin
PhD Candidate, March '18
Detecting Cosmic Rays with the Murchison Widefield Array.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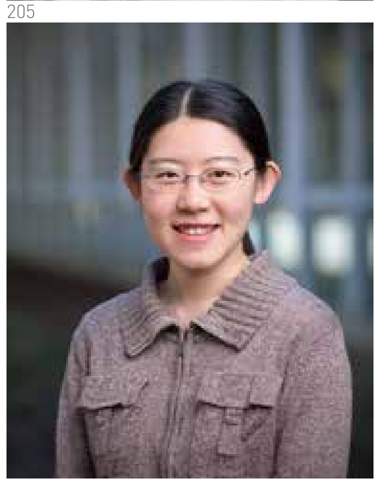
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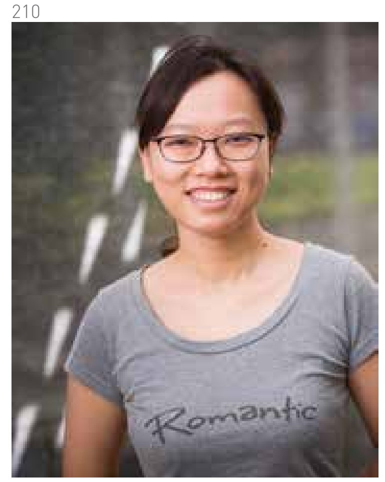

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O. Ivy Wong, ICRAR-UWA
Research Fellow, March '14
Physical processes of star formation & galaxy evolution; Growth of supermassive black holes; Multiwavelength observations (X-rays, UV, optical, IR, radio); All-sky radio surveys (HI and continuum); Citizen science (Radio Galaxy Zoo); Machine learning applications to radio astonomy.

206

Ruby Wright, ICRAR-UWA
PhD Candidate, August '18
The comprehensive treatment of gas in semi-analytic models of galaxy formation.

207

Chen Wu, ICRAR-UWA
Senior Research Fellow, March '11
Data-intensive astronomy; SKA Dataflow optimisation; Machine learning.

208

Mengyao Xue, ICRAR-Curtin
PhD Candidate, November '15
Southern Pulsar Census and Polarimetric Studies with the MWA.

209

QingZeng Yan, ICRAR-Curtin
PhD Candidate (submitted), November '15
Molecular Clouds in the Milky Way.

210

Matthew Young, ICRAR-UWA
Astronomy & Astrophysics Course Coordinator, September '09
Coordination of the Astronomy and Astrophysics Coursework; Teaching; Outreach.

211

Songbo Zhang, ICRAR-UWA
Visiting PhD Candidate, February '17
Single pulse studies in high energy astrophysics.

212

Xia Zhang, ICRAR-UWA
PhD Candidate, May '17
Quantitative evaluation of sparse transforms for SKA-scale data processing.

213

Xiang Zhang, ICRAR-Curtin
PhD Candidate (submitted), November '15
Detecting radio emission from meteors with the MWA.

CSIRO's Australian Square Kilometre Array Pathfinder in silhouette against the setting Sun at the Murchison Radio-astronomy Observatory, Australia's SKA site.

8
END MATTER

117 On the horizon

On the horizon

The next five years—2019-2024—is the five years ICRAR has been planning for since day one.

The SKA project will become an intergovernmental organisation, and construction will begin on the ambitious project by 2021. During this period, there will be a lot of opportunities for ICRAR associated with the SKA. The Centre will also engage more broadly with industry, to ensure ICRAR's capabilities can be translated for industrial and community impact.

It is a coming of age for ICRAR, and a transition to a stage where the Centre will interact with a much broader community of individuals, organisations and companies than it has in the past. ICRAR has established itself as an important element not only in the SKA landscape, but also the Australian academic and research landscape, and as a leader in industry engagement.

One of MeerKAT's 64 antennas that make up the SKA-mid precursor in South Africa's Karoo region. Credit: SKA South Africa.

The period ahead represents the opportunities that ICRAR has been training for over the last decade, and the Centre's future is tied to making the most of the scientific opportunities presented by the SKA. The Centre is, and will remain, a leader in using the SKA precursors, as well as a planner and designer for the future. It is a very exciting time, and one that will see ICRAR attain a long-term and sustainable future.

It is hoped that before the end of this five-year period, we will see the first trickle of SKA data coming into ICRAR—first light for the telescope. ICRAR will be there to get the most out of the SKA, for Australia and for the Centre's partners.

2017–2018