Australian Academy of Science

NATIONAL COMMITTEE FOR **ASTRONOMY**

Decadal plan for Australian astronomy 2016–2025

Mid-term review

Acknowledgements

Thank you to Chair and members of the Mid-term Review Committee, who have worked tirelessly to bring this report to publication. Thanks also extend to the membership of the Capabilities and Opportunities Review Committee and to the National Committee for Astronomy, who have all contributed significantly to its development, and to the members of the astronomy community who contributed, whether that be by hosting or attending a consultation workshop, providing input or by contributing photos to help this plan truly reflect the breadth of Australian astronomy.

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Australian Academy of Science

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Front cover image: Seeing Stars Art Prize was a celebration of art and astronomy inspired by the world's largest telescope—the Square Kilometre Array (SKA), which will be co-hosted here in Australia. Using the inspiration of the SKA, artists were invited to create original pieces of artwork expressing the excitement and mystery of the SKA and its potential for discovery. More than 2 300 entries were received.

Listening by Alice Pulvers, SKA Art Prize 2013, SKA Project Director's Choice Award. 'Do we live in a universe or is there a multiverse? We began with a bang 13.72 billion years ago and are surrounded by hundreds of billions of galaxies. Our knowledge of space–time has expanded greatly over the past century. Technology has allowed us to discover, explore and theorise about the mysteries of our universe at the very small and very large scale. Compounds, atoms and subatomic particles have been discovered. Do strings underlay all of our subatomic particles? The mystery of dark matter and dark energy are perplexing us today. Is this matter that we are detecting from another universe? This painting explores these ideas of space, time, multiverse, matter, strings and our planet.'

Back cover image: CSIRO's Australia Telescope Compact Array (ATCA) under the Milky Way. CREDIT: CSIRO

Prepared by the National Committee for Astronomy on behalf of the Australian Academy of Science.

All URLs supplied in this plan were viewed July 2020 and were correct at the time of publication.

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Two astronomers gaze in wonder at the night sky. CREDIT: KIM STEELE, ICRAR

Section 1:

Executive summary

The 2016–25 decadal plan for astronomy outlines six fundamental science questions, and details the major facilities and infrastructure required for Australian astronomers to play a world-leading role in answering those questions. Enormous progress has been made in the five years since the plan was written. Australian astronomers have made the most stringent measurements of the Epoch of Reionisation, examined the dynamics and chemistry of galaxies in the nearby and distant Universe at unprecedented spatial resolution, led the world in the discovery and identification of intense bursts of radio waves from the distant Universe, probed newly discovered exoplanets, and been involved in the discovery and follow-up observations of astrophysical sources of gravitational wave radiation.

This progress has been underpinned by the nation's excellent telescope and computing facilities, the excellence of research staff, and the superb cohort of students that they train. The Australian Government's investment in a strategic partnership with the European Southern Observatory (ESO) has put the nation on the path to full ESO membership. This partnership is unleashing major Australian-led science programs on the world's most capable optical observatory. The Square Kilometre Array (SKA) pathfinder facilities have been outstandingly productive, providing fundamental new scientific opportunities. These new optical and radio facilities have also allowed Australian institutions and companies to develop and demonstrate key technologies and engage in world-class, multi-million dollar instrumentation and technology projects for future facilities (such as the SKA and the Giant Magellan Telescope) and current facilities (such as MAVIS for the ESO VLT and 4MOST for ESO VISTA). Technology spin-offs have included new techniques in space situational awareness, reducing vibrations in harsh environments, improving the output of solar farms, and the application of advanced data analytics, including for COVID-19 clinical data processing.

Meanwhile, the university community and international partners have stepped in to fill funding gaps in the operation of domestic facilities such as the Anglo-Australian Telescope, while merit-based access to the Parkes Telescope has been maintained with external contracts for Parkes time covering day-to-day operating costs. The theory and observational communities are being well supported by ongoing major upgrades to national supercomputing infrastructure at NCI and Pawsey.

The most significant recent astronomical discovery has undoubtedly been the detection of gravitational waves, initially from black-hole mergers, then from a neutron-star merger. Combined gravitational wave and electromagnetic observations have been able to provide localisation and identification for the latter, with Australian facilities playing a unique and important role in this field. Major new opportunities have also arisen in the last few years, including the formation of the Australian Space Agency, and the increasing importance of high-performance computing (HPC), data centres, and federated astronomical datasets. Building on recent successes and making use of new opportunities, the major recommendations in this mid-term review follow.

Mid-term review recommendations

- Achieve full membership of the European Southern Observatory at the earliest opportunity, and well before the current strategic partnership ends in 2027.
- Protect the substantial national investment by supporting the completion of the Giant Magellan Telescope (GMT), including funding of GMT instrumentation built in Australia.
- Pursue realisation of the full Square Kilometre Array Observatory, while continuing to exploit its ASKAP and MWA pathfinders.
- Continue supporting world-class national instrument development capabilities that maximise Australia's engagement, influence and return from global projects.
- Continue investment in training people with strong scientific and translatable skills.
- Establish a long-term, sustainable, distributed and interoperable set of HPC and data centre arrangements that span the requirements of gravitational wave, radio, optical, and theoretical astronomers, and provide funding for commensurate training and education in data science and code development.

- Fund the design and development of an Australian gravitational wave pathfinder to lay the foundations for a future southern hemisphere detector hosted by Australia.
- Explore mechanisms to build stronger ties between the Australian astronomy community, the wider Australian space science community, and the Australian Space Agency.
- Pursue data access to the Legacy Survey of Space and Time via the exchange of time on Australian national facilities.

A traditional area of strength in the Australian community has been collaboration between communities utilising diverse techniques, including optical/infrared, radio, theory, high energy and Antarctic astronomy. This cooperation positions Australia to exploit future multi-wavelength and multi-messenger opportunities—especially in the field of transient science, the study of short-lived astronomical events. Further linkages and engagement with international facilities that complement domestic facilities are encouraged.

The decadal plan's community goals in education, training, industry and gender balance remain highly relevant. In some cases, progress has been slower than expected. Further contributions to STEM education and better awareness of wider issues of gender, cultural and linguistic diversity, and disability and illness have been identified as areas that require more community attention. A significant new area of community concern is the carbon footprint of astronomers and the wider issue of sustainability. We make several detailed recommendations in this mid-term review in order to reduce the carbon impact of research. These include the expansion of remote observing facilities, the development of meeting and conference capabilities to enhance remote participation experience, and the use of more energy efficient HPC systems and software.

COVID-19

The drafting of this mid-term review coincided with the first five months of the global COVID-19 pandemic. Although the responses of Australian governments and people have been exemplary in avoiding a medical and economic catastrophe at the time of publication, the repercussions of the pandemic are expected to extend well into the remainder of the decadal plan period.

Government budgets around the world, including Australia, will be tight in the coming years. Funding opportunities for research and research infrastructure may be reduced. Decreased revenue from international student enrolments may lead to a reduction in the ability of universities to hire and retain teaching and research staff. Career progression for PhD students and early-career researchers will be more difficult. Conferences, workshops and face-to-face meetings, where astronomers have mutually benefited from knowledge-sharing, will be more challenging. Many of the world's observatories, especially those with high staffing levels, will be closed for a significant part of 2020.

These challenges remain to be faced. However, on the positive side, astronomers have been able to contribute in a significant manner to mitigating the COVID-19 emergency. Their data analytic skills have been helpful in assisting with clinical epidemiological studies and COVID-19 monitoring.

One such astronomer is University of Queensland researcher, Samuel Hinton, who has been the lead data analyst for the COVID-19 Critical Care Consortium, with representatives from over 40 countries. Samuel constructed and maintained a data science pipeline which was responsible for ingesting raw clinical data from hospitals around the world, then cleaning, standardising and processing the data into useful products for machine learning and statistical analysis. Sam also built and maintained an interactive dashboard which provided a data summary for clinical teams. Further work is planned on causal modelling and treatment outcome prediction.

Another Australian researcher, Swinburne Laureate Fellow Professor Matthew Bailes, organised an OzGrav hackathon which developed a web-based survey, BeatCovid19now*, for the Centre for Global Health and Equity on the symptoms of COVID-19 and to provide demographic information. Statistical and visualisation support tools were provided by the research group of Laureate Fellow and Australian Academy of Science Fellow Professor Karl Glazebrook and staff from the Gravitational Wave Data Centre, in collaboration with the private sector including the Arq Group. BeatCovid19now has so far been completed over 30,000 times across about 100 countries.

* https://beatcovid19now.org

Section 2:

Australian astronomy 2016–2020

Highlights of the first five years of this decadal plan period include Australia's new partnership with the European Southern Observatory (ESO), the signing of the international treaty to form the Square Kilometre Array (SKA) Observatory, groundwork laid for the next generation of optical/infrared extremely large telescopes, and the founding of two ARC centres of excellence. There have been major scientific breakthroughs in the first detections of gravitational waves, the possible detection of the 'Cosmic Dawn' when the first generation of stars burst into life, an extraordinary growth in the rate of exoplanet discoveries, and the first identifications of the host galaxies of fast radio bursts.

Swinburne University's Professor Jarrod Hurley gazes upon the OzSTAR Supercomputer. OzSTAR is housed at Swinburne and plays a key role in the computational efforts of OzGrav, the ARC Centre of Excellence for Gravitational Wave Discovery. CREDIT: KARL KNOX / OZGRAV

THE DISCOVERY OF GRAVITATIONAL WAVES

Australian physicists and astronomers were an integral part of the 2015 discovery of gravitational waves from a binary black hole in-spiral by the LIGO consortium. This first discovery was a momentous occasion in the history of physics and astrophysics. Despite having been predicted 100 years earlier, it was the first time the faint ripples of these waves had been detected, and in 2017 the discovery earned a Nobel Prize in Physics.

Australians played an even greater part in a later event in 2017, where a pair of neutron stars coalesced, leading to the near-simultaneous detection of the electromagnetic radiation and the localisation of the host galaxy, NGC 4993.

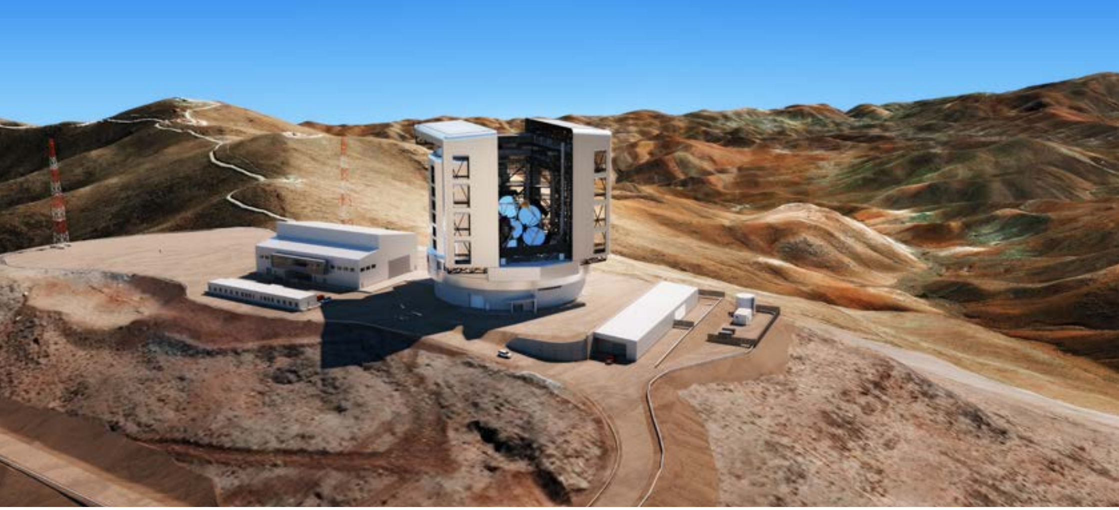
Since then, numerous other events have been observed and Australian astronomers and physicists are at the forefront in designing instrumentation and algorithms and inferring astronomical information from these events, principally through the new ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav).

2.1 The Australian landscape

The first five years of the decadal plan has seen substantial evolution in the national astronomical landscape. In 2017, Australia entered into a 10-year strategic partnership with the European Southern Observatory (ESO). This partnership provides Australian astronomers with access to the facilities of ESO's Paranal and La Silla observatories—most notably the four 8-metre telescopes of the ESO Very Large Telescope (VLT)—on the same basis as astronomers based in ESO member nations. This was a significant event, which directly addressed the plan's goals for 8-m class telescope access equivalent to 30% of a single 8-m telescope, albeit only to 2027.

The partnership with ESO has substantially restructured the funding for Australia's portfolio of optical/infrared astronomical facilities. The most obvious result has been the restructuring of the Australian Astronomical Observatory. The governance and funding of the 3.9-m Anglo-Australian Telescope (AAT) has—for the seven-year period 2018 to 2025—been successfully transferred to a consortium of 13 universities (the AAT Consortium), which has contracted with the Australian National University (ANU) to operate the AAT. The instrumentation components of the previous observatory have been transferred to a new Australian Astronomical Observatory (AAO) Consortium, comprising Macquarie University, ANU, the University of Sydney and Astronomy Australia Limited (AAL). These new arrangements have seen the AAT continue effective operations on a

CSIRO's Australian
Square Kilometre Array
Pathfinder (ASKAP)
under the Milky Way.
CREDIT: CSIRO



Rendering of the Giant Magellan Telescope showing the design of the telescope, enclosure and summit in 2019. Produced by M3 Engineering. CREDIT: GIANT MAGELLAN TELESCOPE – GMTO CORPORATION

reduced budget, while the new AAO has gone on to successfully compete for significant new ESO contracts. The ESO partnership has allowed Australia to halt its purchase of time on the twin 6.5-m Magellan telescopes of Las Campanas Observatory in Chile.

The past five years have seen important progress in the development and support for both of Australia's pathfinder instruments for the Square Kilometre Array (SKA): the Murchison Widefield Array (MWA) and CSIRO's Australian SKA Pathfinder (ASKAP). These are deploying technologies and developing the site that is key for the massive international SKA science project, delivering return to the nation in the form of both significant construction in Western Australia, and commercial spinoffs from new technologies such as using MWA to track space debris.

ASKAP has now transitioned to operations mode, with data from early science, pilot surveys, and observatory projects resulting in the publication of high-impact science. Examples include the detection of cold gas outflow in the Small Magellanic Cloud, measurement of the baryon content of the Universe, and near-completion of the Rapid ASKAP Continuum Survey (RACS). The MWA has continued to expand, increasing both in size and scope of its science capabilities. The team has published world-leading results across a broad suite of science programs, including a low-frequency catalogue of 300,000 radio sources, and the world's most stringent limits on signals from the Epoch of Reionisation. The development of the world-class Murchison Radio-astronomy Observatory

(MRO), home to both ASKAP and MWA, has also allowed the deployment of a suite of other radio facilities, including the EDGES single-element antenna that reported the possible detection of the 'Cosmic Dawn', the era when the very first stars formed in the Universe. It also hosts SKA verification systems that have been critical steps on the path to the SKA-Low, whose construction will shortly commence at the MRO.

2.2 The international landscape

The international astronomical landscape has also continued to evolve over the last five years. The next generation of extremely large telescopes (ELTs)—the European ELT, the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT)—are all moving towards construction. All three telescopes are now in a critical phase as they refine project plans and cost estimates, secure locations, and firm up funding sources. Substantial ground works have been completed at the secured sites of both the GMT and European ELT. Substantial construction contracts have been awarded by all three projects, and major advances have been achieved in the selection and design of the planned first-light instrumentation suites, but challenges remain.

In 2019, Australia, China, Italy, the Netherlands, Portugal, South Africa and the United Kingdom signed the international treaty which formally established the Square Kilometre Array (SKA) Observatory, transitioning the SKA organisation from a private, non-profit company into an intergovernmental treaty organisation. The SKA will be split over two sites, with Australia hosting the low-frequency array (50 – 350 MHz) and South Africa hosting the mid-frequency array (350 MHz – 15.3 GHz). Key decisions have now been made on SKA's budget and capabilities, with construction of both arrays due to begin in 2021, with full operations scheduled for 2029.

The Laser Interferometer Gravitational-wave Observatory (LIGO) began operations in 2015, followed shortly by the announcement of the first detection of gravitational waves from an astronomical source—the merger of two black holes. The first detection of gravitational waves from the merger of two neutron stars, accompanied this time by a matching electromagnetic detection and host galaxy detection, occurred in 2017. This single event confirmed that neutron star mergers are an important source of heavy elements, that gravity travels at the speed of light, and enabled a brand new type of measurement of the rate of expansion of the Universe. During 2019 and early 2020, LIGO and its European partner Virgo were announcing new detections almost weekly.

The Atacama Large Millimeter/submillimeter Array (ALMA) has continued to provide fundamental new information on the composition and dynamics of objects ranging in scale from nearby comets to high-redshift galaxies. ALMA was part of the Event Horizon Telescope which produced the first direct visual evidence for a supermassive black hole and its shadow in 2019.

Construction of the USA's Vera C. Rubin Observatory on Cerro Pachón in Chile is now well advanced. When it starts operating in 2023, the 8.4-m telescope of the Rubin Observatory will deliver the revolutionary Legacy Survey of Space and Time (LSST). Re-imaging the entire visible sky roughly every 3 nights at a data rate of ~15 TB every night, this survey will deliver a unique set of data containing millions of transient sources every night, plus a multi-colour map of the southern sky to unprecedented depths.

Other international facilities in which there is substantial Australian science interest, and which are either operating now, or scheduled to become available before 2025, include the eROSITA X-ray telescope, the James Webb Space Telescope (JWST), the Cherenkov Telescope Array (CTA), and northern 8-m class telescopes including Keck and Subaru.

2.3 The scientific landscape

The above developments in the national and international facility landscape have occurred concurrently with a series of remarkable scientific advances—developments in which Australian researchers have played multiple key roles, and which will form the context in which research programs for the rest of this decadal plan (and the following decadal plan) will take place.

The Nobel-Prize-winning first detections of gravitational waves have ushered in the age of gravitational wave astronomy, and crystallised in the international scientific community the concept of 'multi-messenger' astronomy—integrating multiple and independent detection mechanisms, including traditional electromagnetic observations, high-energy particles and photons, and (now) gravitational waves. The formation of the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav), combined with the extensive engagement of Australian researchers in follow-up observations of these initial discoveries, reflects the emerging importance of this field as a future research priority.

The first localisation of the source of a non-repeating fast radio burst—FRB180924—was made by ASKAP in 2018. FRBs are transient radio pulses with

EXCELLENCE IN SCIENCE

Australia is positioning itself as a key player in international astronomy with the recent creation of two centres of excellence.

ASTRO 3D: the ARC Centre for All Sky Astrophysics in 3 Dimensions is led by Australian Academy of Science Fellow Professor Lisa Kewley at the Australian National University. The centre aims to answer fundamental questions associated with the origin of matter and the periodic table of elements, and the origin of ionisation in the Universe using innovative 3D technology. It involves five other Australian universities, one research organisation, and six overseas institutes

OzGrav: the ARC Centre of Excellence for Gravitational Wave Discovery is led by Professor Matthew Bailes at Swinburne University of Technology. OzGrav seeks to capitalise on the historic first detections of gravitational waves to understand the extreme physics of black holes and warped spacetime. The centre includes five other Australian universities, one research organisation, and seven overseas institutes.

Together, these centres of excellence have more than 400 members and have propelled Australian research in these areas onto a world stage. They have already provided excellent training and employment opportunities for numerous postdoctoral researchers and PhD students, and considerable education and outreach experiences for the community.

These centres are building on the ground-breaking achievements of the ARC Centre of Excellence for All-sky Astrophysics, known as CAASTRO (2011–18).

durations of a few milliseconds. The physical processes that can cause a burst that is both so bright, and so short, remains unknown. But the identification of their host galaxies is key to unravelling this mysterious class of sources. The combination of widefield, rapidly-time-sampled data from Australian radio telescopes such as ASKAP and optical follow-up facilities such as ESO have been powerful tools in unravelling these elusive sources, using them as a probe of the diffuse intergalactic medium, and uncovering the 'missing' ordinary (baryonic) matter in the Universe. The recent detections of gamma-ray bursts by ground-based gamma-ray telescopes (HESS and MAGIC) additionally herald a new era of extraordinarily rich photon statistics for studies of such transient sources at the highest energies.

International interest in the early Universe was further bolstered by the reported detection of a Cosmic Dawn radio signal produced by the births and deaths of the first generations of stars, and by new constraints on the subsequent Epoch of Reionisation, during which the intergalactic medium was transformed from neutral to ionised by early sources of ionising radiation. The Cosmic Dawn experiment was performed by the US-operated EDGES antenna located at the Murchison Radio-astronomy Observatory (MRO). Australia's MWA, the Dutch LOFAR, and the US-operated PAPER telescope have all reported limits on the amplitude of the radio hydrogen signal during the later Epoch of Reionisation. These multi-redshift experiments have constrained models of the formation and evolution of structure in the first billion years of the Universe, and ruled out some astrophysical models of the evolution of structure.

Between 2014 and 2018, NASA's Kepler space telescope continued its paradigm-changing program of exoplanet discovery via transit detection in a new form as the K2 mission—discovering thousands of exoplanets in selected fields across the sky. As Kepler/K2 was ceasing operations in 2018, NASA's Transiting Exoplanet Satellite (TESS) mission took over with another revolutionary survey for exoplanets. By the end of 2020 TESS will have surveyed almost the entire northern and southern skies for exoplanets orbiting bright stars—stars bright enough to allow the follow-up ground-based observations to measure both masses and sizes (or equivalently densities), telling us whether these small, potentially habitable planets are rocky, icy or gaseous. Australian research teams have geared up to exploit the flood of photometric data emerging from these NASA missions to address key questions about the nature of stars and their planets.

The first and second releases of data from ESA's Gaia mission occurred in 2016 and 2018 respectively. This powerful astrometric satellite is measuring billions of precise positions for unresolved sources in our Galaxy (i.e. stars) and external to our Galaxy (mainly quasi-stellar objects, or QSOs). The former is delivering proper motions and distances for some 1.3 billion stars, whilst the latter links the coordinate reference frames used by radio and optical astronomers with unprecedented levels of precision. These data have had revolutionary impact across all areas of stellar and Galactic astronomy, revealing, for example, that the low-metallicity halo component of our Galaxy is actually composed of two distinct and different source populations. These Gaia data are massively multiplying the value of huge Australian spectroscopic surveys of our Galaxy, and this value-add will only increase as subsequent data releases (with more precise distance estimates to yet more stars) continue over the next five years.

Section 3:

2016–2025 decadal plan

3.1 Infrastructure priorities

The 2016–25 astronomy decadal plan—'Australia in the era of global astronomy: The decadal plan for Australian astronomy 2016–2025'—identified the following infrastructure priorities:

Goal: Partnership equating to 30% of an 8-m class optical/infrared telescope.

Achieved. A 10-year strategic partnership with ESO commenced in 2017, providing access to the facilities of ESO's Paranal and La Silla Observatories, and in particular to the four 8-m telescopes of the Very Large Telescope (VLT) at Paranal. This represents potential access to 30% of a single 8-m class telescope through to the end of the strategic partnership in 2027.

Goal: Continued development and operations of Square Kilometre Array (SKA) precursors, the Australian SKA Pathfinder (ASKAP) and Murchison Widefield Array (MWA) at the Murchison Radio-astronomy Observatory (MRO), and membership of the SKA telescope.

Achieved. ASKAP is now functioning in operations mode with all antennas, though with limitations to the data collection and processing rate. MWA Phase II commenced operations in 2016/17. Australia signed the SKA Observatory Convention in March 2019.

Goal: Partnership equating to 10% of a 30-m class optical/infrared extremely large telescope (ELT), such as the Giant Magellan Telescope (GMT).

Partially achieved. The GMT Project is moving steadily towards construction. A recent external baseline review highlighted the strength of the GMT Project team and their ability to build this telescope. The key issue now for GMT is securing the remaining funding required to complete the telescope from a combination of the US National Science Foundation, current partners, new

A 20-second exposure showing the Milky Way over the Aperture Array Verification System (AAVS) station in Western Australia, a testbed for Square Kilometre Array technology.
CREDIT: MICHAEL GOH AND ICRAR/CURTIN.

partners, and US philanthropists. Access to a completed GMT at the 6% level is assured through Australia's previous investment. Some combination of further capital investment in GMT (potentially through the construction of instrumentation in Australia), or full ESO membership (making Australia a partner in the European ELT), or both, will be required to raise that share to 10% of a 30-m class telescope.

Goal: Capability within the national observatories (AAO, ATNF) to maximise Australia's engagement in global projects through instrumentation development for these and other facilities.

Partially achieved. The restructuring of the AAO from an Executive Agency of the Department of Industry, Science, Energy and Resources (DISER) to the AAO Consortium (involving Macquarie University, Australian National University, University of Sydney and AAL) has secured an investment in instrumentation capability through to 2027. Contracts between both ESO and GMT with the AAO Consortium are underway. The Australia Telescope National Facility (ATNF) instrumentation program has now completed ASKAP construction and relies on CSIRO funding for development of new technology and instruments, supplemented by project-based external funding.

Goal: World-class high-performance computing (HPC) and software capability for large theoretical simulations, and resources to enable processing and delivery of large data sets from these facilities.

Partially achieved. Investments by AAL/NCRIS, CSIRO and DISER in optical, radio, gravitational wave, and SKA data centres has expanded data science capabilities and access to HPC time over the first half of the decadal plan period. Funding for a refresh of the NCI and Pawsey facilities has been committed. However, the availability of HPC time remains short of the level considered internationally competitive by the Australian theory and simulation community.

3.2 Community priorities

The decadal plan identified four key community priorities for engagement and broader impact:

Goal: Utilisation of astronomy to improve participation and the standard of science education in schools through teacher training programs.

Partially achieved. Programs led by CAASTRO, ASTRO 3D, OzGrav, CSIRO and ICRAR are contributing to improving the quality of science education in schools. OzGrav's Mission Gravity! is one example, delivering astronomy education into the classroom while also supporting teachers to deliver the material themselves.

Goal: Provision of graduate training that includes transferable skills to provide highly skilled graduates for roles in wider society.

Partially achieved. Well-funded internship programs and centre of excellence programs are contributing to graduate training, especially in the area of data science skills. More needs to be done to reach a wider graduate community.

Goal: Establishment of a central body to promote and facilitate industry engagement with the next generation of global facilities.

Not achieved. Membership of ESO and the SKA has resulted in the appointment of industry bodies for the purpose of information sharing. Optical (ESO) and radio (SKA) partnership/membership management has been consolidated

High school students visiting Swinburne University explore the universe in virtual reality as part of OzGrav's Mission Gravity. CREDIT: CARL KNOX / OZGRAV

within a single department within DISER. This will potentially increase the ability of industry to interact with Big Science.

Goal: Adoption of principles and practices that aim for at least 33% female representation at all levels of Australian astronomy by 2025.

Partially achieved. Many institutes now have equity and diversity action plans which are aligned with this priority, with strong engagement with the SAGE Athena Swan initiative to address gender imbalance. This work was preceded by the establishment of the Pleiades Awards by the Inclusion, Diversity and Equity Chapter of the Astronomical Society of Australia. Some institutes have improved their gender balance through standard hiring processes, while others have made (or committed to make) female-only faculty hires.

Section 4:

Demographics, impact and engagement

4.1 Demographics

A survey of the astronomy community leading up to the launch of the 2016–2025 decadal plan reported a total of 248 fixed-term research staff (227 FTE) and 139 (122 FTE) ongoing research staff working in the field of astronomy in 2014[1]. Twenty-one percent of the total were women. The number of astronomy PhD students was reported as 266, of whom 33% were women.

For the mid-term review, the National Committee for Astronomy commissioned a brief survey of department heads in late 2019 to provide a snapshot of current demographics. Responses were received from all institutes contacted. A total of 204 fixed-term staff (202 FTE) and 166 (164 FTE) ongoing research staff were reported. Compared with 2015, this represents a small decrease in the total number of staff and a small increase in total FTEs. The proportion of women researchers has increased to 27%. Interestingly, the proportion of ongoing research staff has also increased from 36% to 45%.

For the first time, the proportion of researchers at different academic (or equivalent) levels was recorded (fixed-term and continuing). The distribution of staff by employment status and level is shown in Figure 1.

The distribution of staff by employment status and gender is shown in Figure 2. In 2019, 40% of level A astronomy research staff were women, but this percentage reduces to 21%, 26%, 20% and 19% for levels B to E, respectively.

One of the largest changes over the last few years seems to have been in the number of astronomy PhD students, which has increased from 266 in 2015 to 326 in 2019, with the fraction of women students remaining roughly constant at 30%. The distribution of research students into PhD, masters and honours (also international), and split by gender is shown in Figure 3.

1 Australian Astronomy Decadal Plan 2016–2025 Working Group 3.1, 2015, Demographic Survey of Australian Astronomy.

Figure 1: Distribution of employment status (fixed-term contract or permanent) by seniority level for Australian astronomy researchers in 2019. Levels A-E corresponds to research associate, research fellow (lecturer), senior research fellow (senior lecturer), principal research fellow (A/Prof) and senior principal research fellow (Prof), respectively.

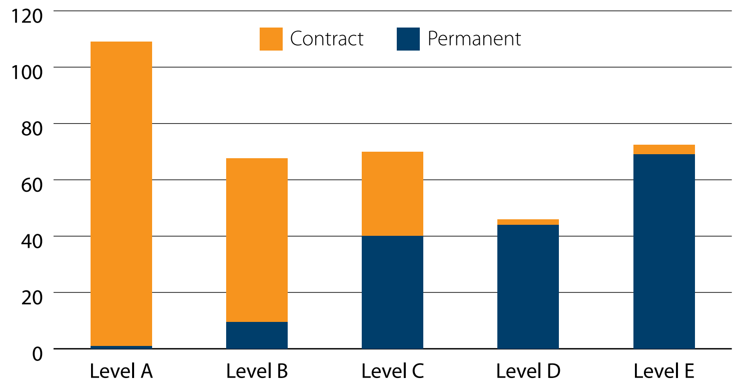


Figure 2: Distribution of gender by seniority levels for Australian astronomy researchers in 2019. Levels A-E are as explained in the Figure 1 caption.

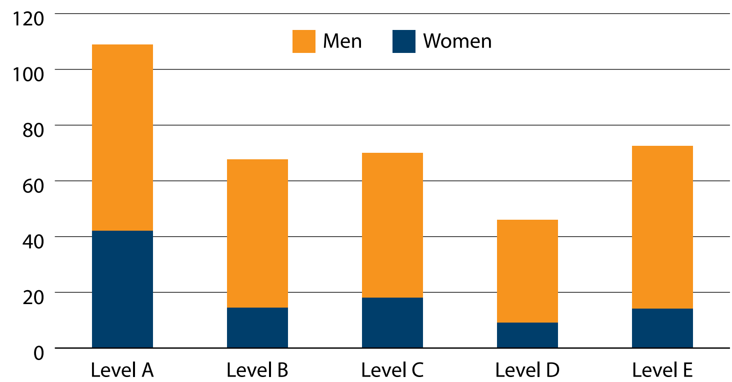
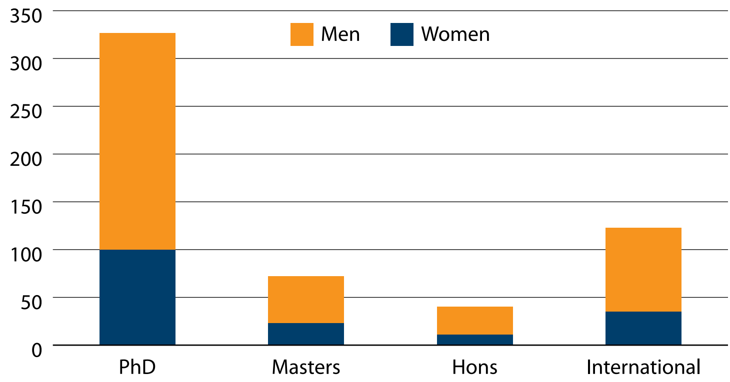


Figure 3: Distribution of gender by type of astronomy student across all Australian universities. International students are a subset of the previous categories (mainly PhD).



4.2 Publications

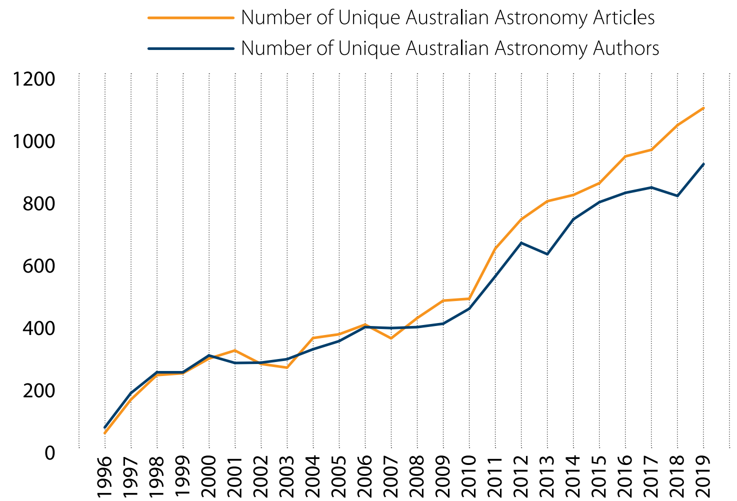
Astronomy publications, techniques and infrastructure were surveyed in 2014 for the decadal plan[2]. Although this was too large an effort to repeat for the mid-term review, a substantial amount of information can be gleaned from a straightforward bibliometric analysis. In many respects, such analyses can be more accurate and objective.

In this study, the NASA/SAO Astrophysics Data System was exploited to extract refereed astronomy publications with Australian authors over the last 25 years, covering three different decadal plan periods, using software provided by Dr Andy Casey[3]. The results are shown in Figure 4. The number of papers published per year has increased four-fold over the last 20 years, and has even increased significantly since the start of the current decadal plan. The former is mainly a result of the increased number of researchers working in the field of astronomy. The number of unique Australian authors (including former staff and students, masters students, and engineering staff) publishing in astronomy journals in 2019 was about 900. Notably, productivity (papers per author per year) has increased by 20–30% over the period covered.

2 Schmidt, B., Wyithe, S., Barone-Nugent, R., 2014, Australian Astronomy Publication and Facilities Survey.

3 https://github.com/andycasey/ads-midterm-review

Figure 4: The number of unique refereed astronomy papers with Australian authors (orange) and the number of unique Australian authors (blue) as a function of time from 1996 to 2019. The data was extracted from the NASA/SAO Astrophysics Data System (ADS) in January 2020. Only papers published in high-impact factor astronomy-only journals (MNRAS, ApJ, ApJS, AJ, A&A, ARA&A and PASA) are included. Address data may be incomplete in ADS, particularly prior to 2000.



Finally, the growth of the field of astronomy in Australia has been accompanied by a growth in national and international collaboration. Nationally, collaborative centres such as ICRAR, CAASTRO, ASTRO 3D and OzGrav have greatly increased numbers of astronomers and improved inter-institutional links (see Figure 5). These centres have also facilitated better international connections, as has partnership in large international facilities (SKA, ESO, GMT) and other science collaborations (Figure 6).

4.3 Astronomy and the physical sciences

The 2018 ARC Excellence for Research in Australia (ERA) study[4] shows that the physical sciences (2008 FoR division 02, which closely corresponds to 2020 FoR division 51) were responsible for 4.4% of Australian competitive grants research

4 Australian Research Council 2018, State of Australian University Research 2018–19 ERA National Report.

Figure 5: The increasingly collaborative nature of Australian astronomy is shown by these plots of the distribution of astronomers and their publication networks over three decadal plans. The marker area is proportional to the number of publishing authors over a three-year period at the beginning of each decadal plan period. The pairwise lines indicate the proportion of Australian papers that involve authors from the linked institutes.

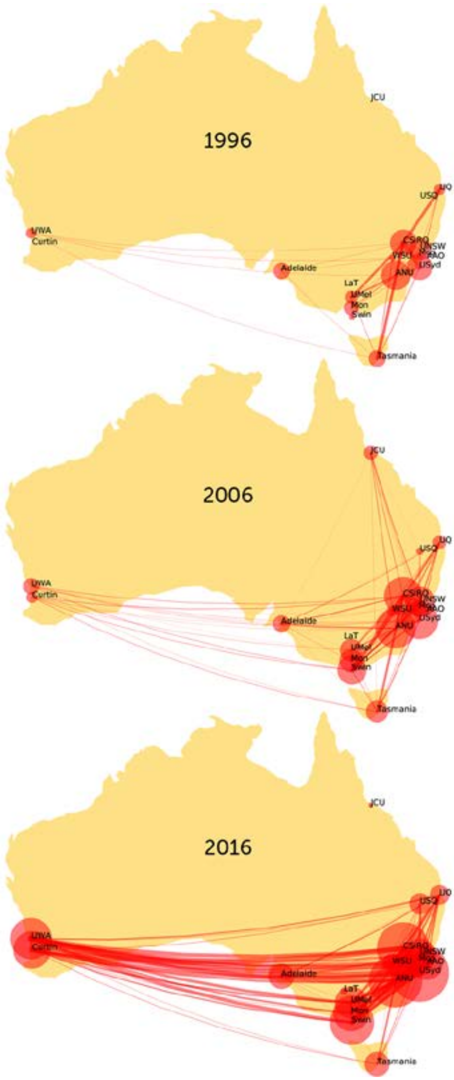
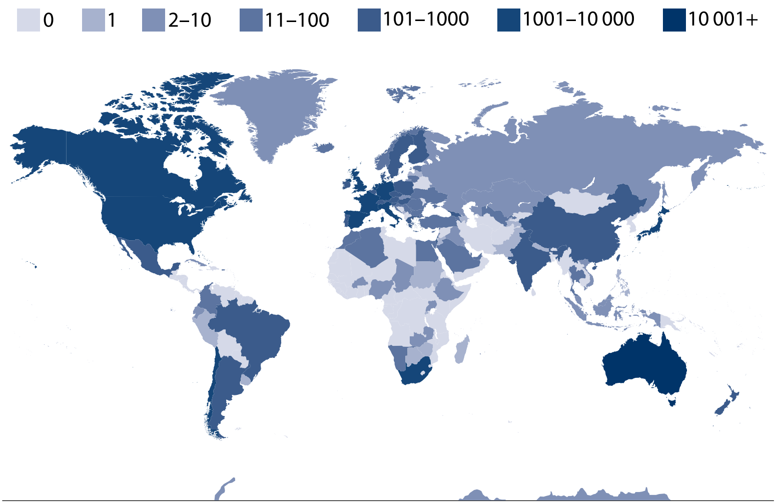


Figure 6: Countries with major astronomy collaboration links with Australia. The map illustrates the number of unique papers from 1996–2019 that involve co-authors from a given country.

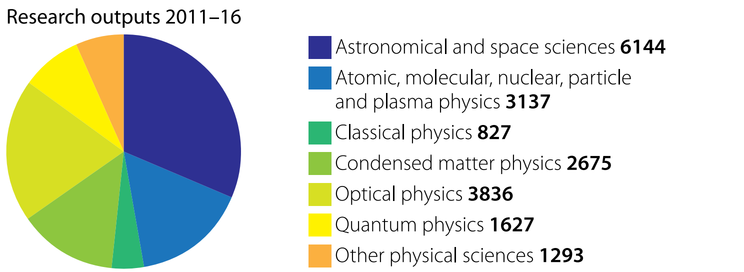


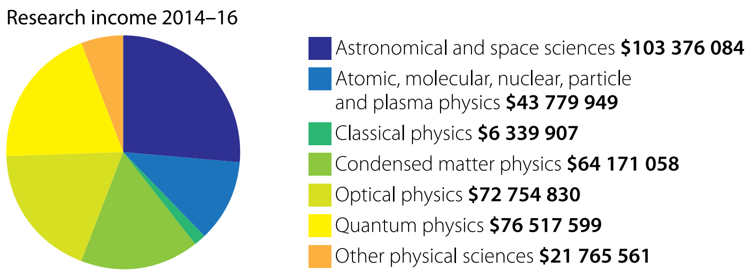
income (HERDC 1) in 2016, 3.6% of the research output and 2.1% of FTEs. Research areas in biology, agriculture, engineering and medicine are understandably much larger than the physical sciences. However, the impact of the physical sciences is substantial. In fact, it is larger than any of the other 22 Australian fields of research, according to ERA 2018. The proportion of 'well-above world average' higher degree research institutes, as measured in ERA 2018, is also the highest for the physical sciences.

A major shift in Australia over the past decade has been the increasing representation of astronomy in the physical sciences. The ERA 2018 report suggests that, among higher degree research institutes, astronomy was the discipline within the physical sciences producing the largest number of research outputs (publications) from 2011 to 2016, the largest research income from 2014 to 2016, the largest source of FTEs in 2017, and made the largest contribution to top-rated (well-above world average) institutes (see Figures 7 and 8).

The corollary of the increasing representation of astronomy in the physical sciences is the onus it places on the Australian astronomy community to make commensurate contributions to the profile of STEM and the uptake of STEM

Figure 7: Research outputs and research income for research groups within the physical sciences division (2008 FoR division 02) over the periods specified (source: ERA 2018).



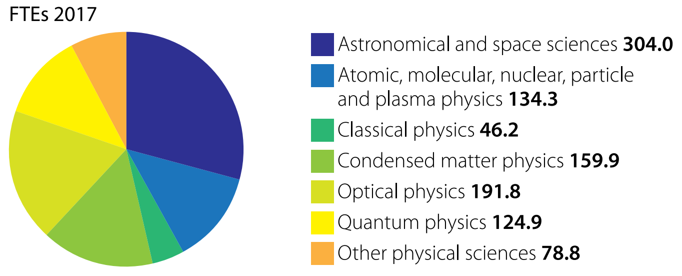


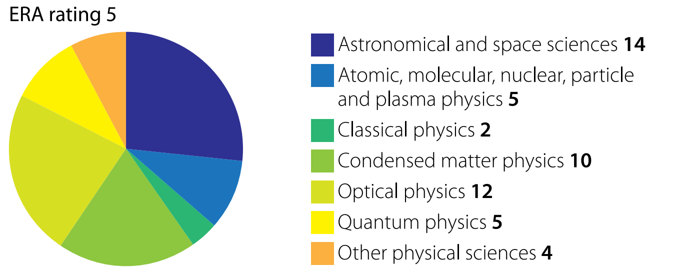
studies in general in Australia; utilise the interest and fascination of astronomy to achieve this; and ensure that the Australian public gets a fair return in investment not only through discoveries and advancement, but also through other societal contributions such as workforce training and translation to industry.

4.4 Funding

The major sources of funding for astronomy research and facilities are universities, CSIRO, the Department of Industry, Science, Energy and Resources (DISER), the Department of Education, Skills and Employment (DESE), and the Australian Research Council (ARC). Universities provide the bulk of the research effort in astronomy. CSIRO Astronomy and Space Science funds most of the domestic radio facilities, alongside research and development activities. DISER funds SKA and ESO activities. DESE supports the National Collaborative Research

Figure 8: FTEs and numbers of top-rated institutes for research groups within the physical sciences division (2008 FoR division 02) (source: ERA 2018).





Infrastructure Strategy (NCRIS), which provides funding for AAL and national supercomputers. In turn, AAL provides significant support for astronomical infrastructure, including eResearch. The ARC funds research projects, research fellowships, smaller-scale infrastructure and centres of excellence, and is the major national source of competitive funding.

The approximate distribution of facility funds (only including major domestic facilities, ESO and other facilities funded by AAL) is shown in Figure 9 over the decadal plan period[5]. National competitive funds from the ARC over the same period are shown in Figure 10. The current funding level for the major facilities is \$45 million per annum. The average astronomy share of ARC funding is \$23 million pa, which is about 3% of available ARC funds.

5 From July 2018, AAT operations transferred from DISER to the AAT consortium. Direct CSIRO operating funding for the ATNF excludes corporate overheads and depreciation (source: ATNF annual reports).

Figure 9: Astronomy funding (in $M pa) for major facilities from 2016 to 2020. Facilities include ASKAP, Parkes and the Australia Telescope Compact Array (operated by CSIRO), the ESO La Silla and Paranal telescopes, the AAT, and facilities and programs funded by Astronomy Australia Ltd (AAL), which include MWA, CTA and eResearch. The AAO instrumentation program is excluded.

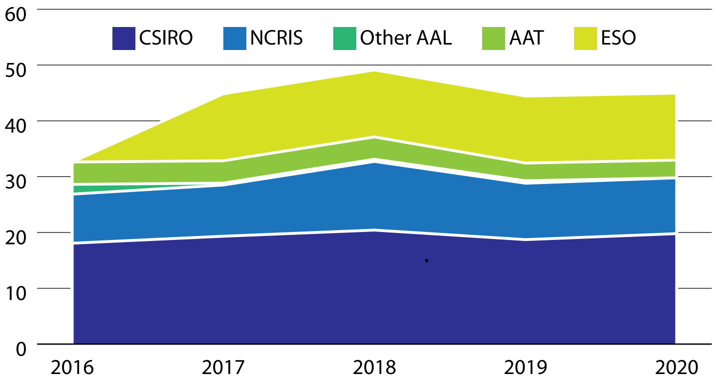
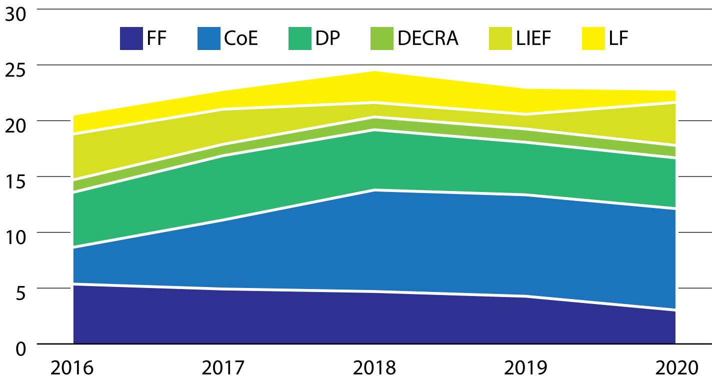


Figure 10: Astronomy funding (in $M pa) from competitive ARC sources (split into Future Fellowships, Centres of Excellence, Discovery Projects, Discovery Early Career Researcher Awards, Linkage Infrastructure Equipment and Facilities, and Laureate Fellowships). Funds are shown per year of distribution (not award).



STARS OF SCIENCE

The Australian Research Council (ARC) supports scientists at the pinnacle of world-class research excellence through the Australian Laureate Fellowships scheme. Since 2016, two astronomers have received this prestigious five-year award, which includes funding for postdoctoral research teams.

Professor Tamara Davis from the University of Queensland is a cosmologist who is helping lead the Australian Dark Energy Survey (OzDES), measuring thousands of supernovae and hundreds of supermassive black holes. The aim of her research is to understand our fundamental laws of nature.

Australian Academy of Science Fellow Professor Karl Glazebrook (inset left) from Swinburne University of Technology studies the evolution of galaxies using advanced instrumentation on the world's largest telescopes. He has developed innovative instrumental, cosmological and computing techniques to further astronomical research.

The scheme supports researchers who will play a significant, sustained leadership and mentoring role in building Australia's internationally competitive research capacity.

Tamara Davis, on the roof of the Anglo-Australian Telescope, which is home to the 2 degree field instrument she and the OzDES team have been using to monitor tens of thousands of sources, such as galaxies, supernovae, and black holes. CREDIT: TAMARA DAVIS

4.5 Education and outreach

The appeal of astronomy has long been a driver of interest for students entering STEM studies. Astronomy ignites wonder and passion, and can be a conduit for introducing students to the broad usefulness of STEM in their education and career choices. STEM skills result in knowledge generation, a more informed workforce with critical thinking skills, increased innovation, enhanced productivity and economic growth. It has been estimated that the advanced physical and mathematical sciences make a direct contribution to the Australian economy equivalent to 11% of GDP[6]. At university, many non-STEM students also take astronomy, which provides them with formal exposure to scientific thinking and methods.

There is also a strong synergistic interaction between education and outreach in astronomy. High-quality education from school through university is critical to maintaining Australian astronomy leadership on the international stage, so professional astronomers see the benefit of extensive outreach. Given the high level of public excitement around astronomy, astronomers keenly feel a sense of responsibility to further engage the public in science. Among the most important tasks astronomers perform is to help the public understand and appreciate science so that they better understand the issues that affect their daily lives.

The last five years has seen an upturn in the public's passion for and interest in astronomy outreach. Major events and the reach of engagement has been better than ever with full-length TV shows such as Stargazing Live and Catalyst, regular morning TV slots, radio interviews, planetarium shows, school outreach, and astronomy tourism such as at Uluru, the Siding Spring Open Day and themed cruises). Fantastic initiatives have been driven by centres of excellence CAASTRO, ASTRO 3D, and OzGrav, such as 'Capturing the Cosmos' for planetariums, CAASTRO/ASTRO in the Classroom, and the Astronomer in Residence scheme at Uluru. Some of these initiatives have also provided professional development opportunities for teachers. Additional initiatives aimed at sharing knowledge about astronomy with Indigenous groups have been undertaken.

6 Australian Academy of Science (AAS) 2015. *The importance of advanced physical and mathematical sciences to the Australian economy*, AAS, Canberra.

Residents of Mt Magnet look through an ICRAR solar telescope at the setting sun with PhD candidate Kathryn Ross. CREDIT: ICRAR

4.6 Training and translation

Professional training in the astronomical community has grown substantially over the last five years, driven by a desire to better equip astronomers for their own work and to better engage with external opportunities. This constitutes both inward-facing training such as astronomical schools, telescope training, coding, publication writing workshops and grant writing workshops, and outward-facing training such as translational skills, coding, data science and job application writing. The availability of media training has also increased through the contributions of individual institutions, CSIRO and the centres of excellence.

Instrumentation and data analysis training such as radio astronomy schools, the ANITA astroinformatics school, and ANITA science-focused school have operated for many years, largely aimed at students and early-career researchers (ECRs). These have been substantially augmented over the decadal plan period by a concentrated effort on software development, coding and data science through the Astronomy Data and Computing Services (ADACS), and supported by the centres of excellence. Scientific writing retreats and training events in proposal writing have also grown under the aegis of ASTRO 3D. Telescope training has partially transitioned from hands-on experience at a telescope site to remote learning and training to use software pipelines, often using big-data facilities and alongside training in data access and analysis tools. The Astronomical Society of Australia's Harley Wood School of Astronomy continues to provide an avenue for students to receive astronomy-specific training, meet and learn from peers, and be introduced to the Australian astronomical community.

The translatable skill set afforded by an astronomy education, particularly excellence in critical thinking and training that targets the ability to analyse data in a methodical scientific manner, is desirable in many industries. Astronomy has provided leadership in the promotion and endorsement of the transition from academia to industry as a strong, viable career path for students and ECRs. Over the past few years, 30% of astronomy graduates have transitioned to data science roles in areas as diverse as banking and finance, robotics, medical research and development including medical imaging and bioinformatics, climate change and meteorology. A significant number are also employed in Australian technology companies and the Australian arms of international technology giants. The aim is to redirect academic culture, such that a non-academic career is perceived to be equally worthy as the traditional academic route. To support this, there has been an increase in coding and data science training, analytics workshops, and job application writing workshops. There has also been an increase in the use of external consultants for these roles, rather than internal training provided by institutions.

4.7 Industry

Astronomical research groups critically rely on expertise in data processing problems at scale, including image and signal processing techniques and expertise in implementing systems that can be accessed over extended partnership networks. This allows them to deliver significant benefits to Australian industries. By partnering with industry and training highly skilled Australians, astronomy provides access to a highly skilled workforce in data science. This gives industry access to expert methodical approaches to problem solving using modelling, mathematics, data sciences, and a deep understanding of physical phenomenology.

Astronomical instrumentation and facility projects can be very large in scale. They allow industry involvement in the construction of astronomical equipment, computing infrastructure, and site construction and engineering including the provision of design, engineering and site services. Partnering with astronomy in such projects allows Australian industry to access a workforce highly skilled in precision instrumentation and engineering design, including advanced manufacturing, electronics, real-time digital system development, sensor design, and interfacing with computing systems.

Companies wanting to be more innovative can access future workforce opportunities through partnership with astronomy. They can engage with graduates and postgraduates in an array of disciplines, using their design and problem-solving capabilities. This is a workforce that is inherently team-based and goal-oriented—core aspects of how astronomical researchers are trained.

The decadal plan envisaged the establishment of 'a central body to promote and facilitate industry engagement with the next generation of global facilities'. While such a body has not been successfully established, AAL has sought to support increased engagement between Australian astronomers and industry partners by supporting a network of 'Industry Champions' in universities across Australia. These champions are academics with experience and success in industry engagement, who can spread the benefits of that experience to other academics through local networks. AAL has also supported multiple rounds of an Industry Engagement Seed Funding scheme that uses small grants to encourage and support astronomers in building partnerships with industry. In addition, within its SKA and Astronomy branch, DISER has engaged a manager in engagement and industry participation with the aim of providing a conduit for Australian industry to engage with Big Science projects such as SKA and ESO.

Australian astronomy has a tangible and substantial track record of success in innovation with industry. Recent examples of collaborations with industry or developments which have industry potential (anti-vibration devices, Puzzle Precision, CloudCAM/Sodar) are included as case studies in this section. Additional examples include:

- **Moku:Lab**, an all-in-one professional test and measurement device that is revolutionising the workbenches of scientists and engineers across the globe. Professor Daniel Shaddock from the ANU and his team of gravitational wave researchers designed and built the device to streamline their own laboratory while researching gravitational wave detection. It can switch between an oscilloscope, spectrum analyser, waveform generator, phase meter, data logger, or lock-in amplifier (and many other functions) from an iPad. They have commercialised it through a company called Liquid Instruments, attracting venture capital and now employing 15 Canberra-based employees. The device is now available in 27 countries and in five languages.

Eduardo Trifoni and David Adams work on a prototype anti-vibration mount at Mount Stromlo. Vibration is a big challenge for future telescopes, and engineers at ANU are creating new solutions to this difficult problem. CREDIT: LANNON HARLEY, ANU

ANTI-VIBRATION SYSTEM MAKES BETTER SPACE IMAGES

To deliver the exquisite images expected from the world's largest telescopes, optics and detectors must be cooled to cryogenic (very low) temperatures. However, until now, the most efficient cryo-cooling refrigeration systems also produced unwanted vibrations that degrade imaging performance.

As part of Australia's engagement with the Giant Magellan Telescope (GMT) project, a team at the Australian National University, working on the GMT's integral-field spectrograph, has developed an anti-vibration mount system that reduces vibration by as much as 100 times more than previously possible. The team is now working with observatories around the world to deploy this system commercially. This technology has potential uses in many applications outside of astronomy by reducing vibration of precision instruments in difficult environments.*

* See video at https://youtu.be/Rm0odzNIKi0

ADVANCED CIRCUIT BOARD MANUFACTURING FOR ASKAP

An example of long-term industry collaboration is CSIRO's ongoing partnership with Newcastle-based small-to-medium size enterprise Puzzle Precision. Puzzle Precision works with CSIRO to design and manufacture tens of thousands of high-end digital circuit boards, consisting of millions of individual components, for the Australian Square Kilometre Array Pathfinder (ASKAP). The phased array feeds on the 36 ASKAP antennas are the most advanced and complex radio telescope receiving systems in the world, and enable astronomers to simultaneously track wide areas of sky in a single observation with great sensitivity.

This collaboration has seen the company more than double in size, improve the production and inspection processes needed for advanced manufacturing, employ many young local people (setting them on career paths in advanced manufacturing) and expand the company's operations into new markets.

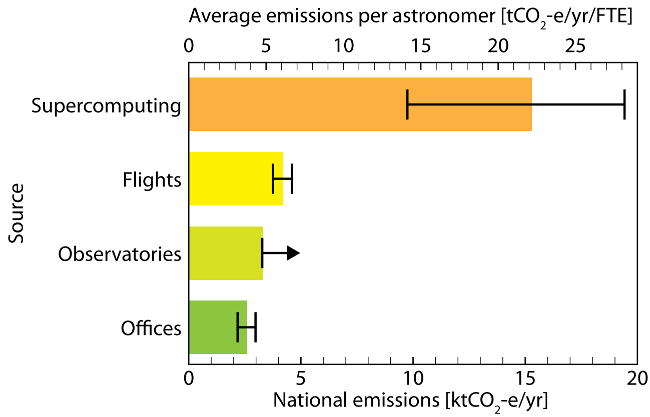
- **GCo Electrical**, a Geraldton-based company with expertise in industrial and infrastructure projects, which has provided civil works for the Murchison Widefield Array, including the installation and commissioning of electrical power systems and the installation of fibre optic cables. They have in the process gained expertise in working in remote, radio-quiet environments, embedding skills in the Western Australian business community relevant to the large-scale procurement and construction needs of the Square Kilometre Array. Shared, two-way upskilling of industry and academia has been an important outcome of work developing, building and operating the suite of radio facilities at the Murchison Radio-astronomy Observatory.

4.8 Sustainability

The impact of Australia's professional astronomy activities on the environment has received recent attention. An active community of concerned researchers has encouraged the discussion of sustainability and carbon footprint within centres of excellence, individual institutions, and the Astronomical Society of Australia. Notable in assessing astronomy's contribution to carbon production are the use of high-performance computing facilities and air travel, which both sit above the national per capita average. A report commissioned for this review estimated that 60% of astronomers' carbon contribution, in their professional capacity, could be attributed to supercomputer usage, while 17% comes from air travel and the remainder from office building power and observatory operations.

Given that the largest share is contributed by supercomputing, the importance of efficient software and sustainable computing solutions is high, especially given the community's desire for further investment in data centres to support large-scale astronomical facilities and big data projects. It is notable that the composition of carbon-positive activities will have changed drastically over the past 20 years, as big data has emerged as a large research component in astronomy.

Figure 11: The estimated carbon footprint of Australian astronomers apportioned into supercomputing, flights, observatory operations and office accommodation. The upper horizontal axis is the footprint of the average astronomer (in equivalent tonnes of carbon dioxide per year); the lower horizontal axis is the astronomy community total (in equivalent kilotonnes of carbon dioxide per year).



CREDIT: ADAM STEVENS

Air travel plays a central role in the culture of the professional astronomical community. It is a time-efficient way to travel large distances nationally, and allows in-person attendance and networking at international conferences and colloquia. Travel to observing facilities has also been perceived as necessary to ensure a deep understanding of the instruments and the best ways to use and improve them, as well as work with local support astronomers. However, this perception has been changing. An example of this has been the wide adoption of remote observing at Australian observatories. In many cases, such as ATNF telescopes, only a computer screen and a good internet connection are required. In other cases such as AAT, dedicated multi-screen facilities have been built at key locations in the major cities—removing the need to travel to telescopes.

MORE EFFICIENT SOLAR AND WIND FARMS

CloudCAM and Sodar are two instruments originally developed by astronomy PhD student Colin Bonner and a team at the University of NSW to remotely monitor site conditions in Antarctica. They are now being sold by a company called Fulcrum3D to improve the efficiency of wind and solar farms.

CloudCAM is providing real-time forecasting for solar energy farms and has resulted in up to 5% improvement in power output, with a 90% reduction in battery usage through its ability to predict when diesel back-up generators need to come online. Sodar is a portable wind monitoring system designed to measure wind speeds in 3D up to 200 m above ground level. It is easy to relocate to different sites, and provides a detailed understanding of wind profiles at each wind farm.

The COVID-19 situation further demonstrated the power of remote research collaboration and remote education. Despite the widespread loss in ability to attend observatories and meetings away from home, researchers in astronomy adjusted to the COVID-19 work-at-home paradigm, having previously used video conferencing and remote collaboration tools for many years. An important area where improvements are required is that of remote workshops and conferences. Such meetings are often where new research is shared among the broader national and international community, knowledge is gained, collaborations are built, training and mentorship is undertaken, and contacts with emerging young researchers are made. But it has not yet proved easy to conduct such meetings remotely with the same level of success.

4.9 Diversity

The issue of diversity in the decadal plan focused primarily on the percentage of female representation in Australian astronomy. While improvements are still required in this aspect, it is also clear that the astronomy community needs to consider a broader range of diversity. This includes supporting initiatives for making universities and scientific institutes safer places for LGBTQIA+ astronomers, providing ally training, providing support networks such as QueersInScience, and providing role models for young researchers. Other initiatives taken by various universities include introducing Indigenous astronomy into outreach and education, and schemes to encourage Indigeneous students to pursue STEM pathways at universities.

A significant national development in this area was the launch of the Women in STEM Decadal Plan in April 2019, a 10-year strategy authored by two learned academies at the request of the Australian Government. The plan seeks to address barriers to STEM participation for women at every point of the STEM pipeline.

There is also the question of cultural and religious diversity. Australian astronomy circa 2020 is still dominated by people of European descent. Australia is a culturally and ethnically diverse country with 26% of us born overseas (from the 2016 Census) and 46% either born overseas or with at least one parent born overseas. Immigration from China and India combined has now overtaken immigration from the UK. The changing demographics in Australia provides a natural opportunity for increasing diversity in the workforce, but the community needs to take care that cultural barriers are removed and that adequate support and respect is given to people of diverse cultures and backgrounds. This goal should sit alongside goals of support for Indigenous students becoming astronomers, and support for LGBTQIA+ astronomers to feel safe and included in their workplaces and at conferences.

Mia Baquiran working on an FPGA board.
CREDIT: CSIRO

Setting up for observing with the Sydney-AAO Multi-Object Integral-Field Spectrograph, at the prime focus of the Anglo-Australian Telescope.

CREDIT: SARAH SWEET

Section 5:

New opportunities

Over the first five years of this decadal plan, significant developments have taken place in a number of areas that were either unenvisaged in the plan, or envisaged but for which the international landscape has significantly changed.

5.1 Gravitational waves

The 2016–2025 decadal plan for astronomy was published in July 2015, just months before the first detection of gravitational waves from the merger of a pair of black holes. Since then we have witnessed a scientific revolution in gravitational wave science. The first discovery in 2015 led to the award of the 2017 Nobel Prize in Physics, after which the first detection was made of gravitational waves from the merger of two neutron stars. This became a 'multi-messenger' event when it was also detected in the electromagnetic spectrum, enabling a wide range of breakthrough science. It confirmed neutron star mergers as a source of heavy elements, confirmed that gravity travels at the speed of light, and enabled a new means for measuring the rate of expansion of the Universe.

The Laser Interferometric Gravitational-wave Observatory (LIGO) and its European partner (Virgo) published 11 gravitational wave source detections in their first two seasons. During their third season (which started in 2019), new detections were announced on an almost weekly basis. Gravitational wave science touches on many of the key science questions highlighted in the decadal plan, including the nature of matter and gravity at extreme densities, how the elements are produced by stars and recycled through galaxies, and the nature of dark energy.

Australian astronomers have been involved in all of these discoveries, either through membership of LIGO/Virgo or via electromagnetic follow-up of the accompanying explosion after the gravitational wave detection. The Siding Spring Observatory 2.3-m, Zadko and Skymapper telescopes, along with AST3-2, ATCA, ASKAP, MWA and Parkes, have all played key roles in this electromagnetic follow-up. These new discoveries have led to new opportunities for funding, including $31 million for the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) in 2017, $2.8 million for the Gravitational Wave Data Centre, and a recurrent $1.8 million pa for the new Centre for Gravitational Astrophysics at ANU. In 2019 OzGrav counted 204 members from across Australia. With the field of gravitational wave science now firmly established in Australia, the next challenge will be to chart a course for Australia's continued involvement in this rapidly growing field over the next half decade, from 2020 to 2025.

Australia has a geographically ideal position for a complementary gravitational wave detector that will require a large international consortium investment. The gravitational wave community already has a considered multi-decade plan with wide community support, to develop and deploy new kinds of gravitational wave detectors in Australia while continuing to have access and influence in international detectors through the strong instrumentation program.

5.2 Space

Space is a rapidly-evolving field with significant opportunities that were not fully anticipated in the decadal plan. The science and technology landscape is being transformed because of the emerging capabilities of low-cost nano-satellites, known as CubeSats with sufficient power, downlink capabilities and attitude control accuracy to carry space telescopes and other astronomy payloads. The Australian sector is well-positioned in this trajectory of rapid global growth thanks to the newly-established Australian Space Agency, which may open both strategic opportunities to participate in international projects and pathways to fund construction of instrumentation for space telescopes.

Space telescopes already play an important role in Australian astrophysics research, accounting for 30% of optical/infrared citation impact-weighted activity (13% total). Australian astronomers have generally participated in space missions by contributing technology, instrumentation or ground stations, the latter of which are important to international space missions thanks to our geographical location. Traditionally, space telescopes have been large and expensive but the transformational technology of shoebox-size CubeSats is changing the types and affordability of missions that can be performed from space.

Australia is well poised to contribute to the next round of technological advancements, driven by the precise needs of astronomy missions. There is

Circumpolar stars over the AAT on a dark winter night. Siding Spring Observatory, NSW.
CREDIT: ÁNGEL R. LÓPEZ SÁNCHEZ

excellent overlap between physics research, industrial applications, and advances in astronomy and astrophysics. There is more incentive than ever to have sovereign space-based capabilities for Earth monitoring, such as relating to climate, fires, agriculture and mining, which shares similar technology to sky-monitoring astronomy missions.

With the increasing congestion of the orbital environment, monitoring and control (space situational awareness) is even more critical to avoid significant damage and loss of productivity from satellite collisions, and to predict and treat sources of radio-frequency interference for radio telescopes. Astronomy can help space science and space science can help astronomy. Together they can enhance opportunities provided by the establishment of the Australian Space Agency.

5.3 Transient science

While most astronomical observations probe persistent and static sources of emission, transient sources necessarily require astronomers and facilities to be responsive. Transients can be diverse in type, including electromagnetic and gravitational waves, and high-energy particles. The opportunities arising from gravitational wave detections, supernovae, high-energy cosmic rays, and radio transients make such science an important component of Australia's future research program. These diverse sources have different observational infrastructure requirements, with geographical location such as longitude coverage and time-sensitive multi-wavelength and multi-messenger considerations important for maximising scientific return. The needs of the transient follow-up community motivate the existence of geographically-distributed, responsive, and multi-wavelength small- to mid-scale facilities with the systems in place to receive alerts and the capacity to provide rapid response. These considerations lend support to maintaining operation of Australia's domestic optical and radio facilities over the next five years, particularly considering that Australia's unique longitude and latitude make it the only location able to provide a prompt response for large swathes of the sky.

Since the decadal plan was published, radio transients such as fast radio bursts (FRBs), gamma-ray bursts, stellar flares and tidal disruption events have emerged as a research strength for Australia, with multiple radio facilities playing world-leading roles. For example, FRBs are short timescale, energetic bursts of broadband radio emission. Their temporal dispersion properties are consistent with the bursts being extragalactic, with unequivocal evidence for their origin to be in distant galaxies. The extreme amounts of energy contained in the signals, and their distant origin, make them ideal laboratories for extreme physics, and as a cosmological probe to weigh the baryons in the Universe. In the global context, the successes of Parkes, ASKAP and UTMOST place Australia as a world leader in the observation and analysis of these bursts. Coupled with access to international 8-m class optical facilities, there have been ongoing and consistent discoveries, furthering knowledge of extreme environments and the interstellar and intergalactic medium, and highlighting the unique capabilities of widefield, high-sensitivity radio telescopes.

Southern hemisphere optical transients, currently supported by the Skymapper telescope, will be significantly enhanced by Rubin Observatory's LSST survey. Aiming to survey the entire southern sky every three nights, the data from this facility will serve a wide suite of science, including multi-timescale transients in

FAST RADIO BURSTS

Australia is a world leader in the discovery of fast radio bursts (FRBs). Archival data from the Parkes telescope in New South Wales enabled the first FRB to be described in 2007, and in 2014 the telescope was the first to observe an FRB in real time. And in 2018, it was the new Australian Square Kilometre Array Pathfinder (ASKAP) telescope which had sufficient sensitivity, resolution and field of view to localise the origin of these bursts to their host galaxies.

Through detection of these bursts with ASKAP, and subsequent measurements at optical observatories, including the Very Large Telescope facility in Chile, Australian astronomers have explained the missing ordinary matter, composed of baryons, in the Universe. They did this by measuring the variable effect of the associated electrons on the arrival times of low-frequency radio waves.

The redshifts obtained at the Very Large Telescope are a powerful example of the effectiveness of Australia's strategic partnership with the European Southern Observatory, without which the credit could easily have been taken by overseas astronomers.

fields overlapping with Australia-based widefield multi-wavelength facilities. New high energy facilities with the ability to detect high-energy gamma-rays and neutrinos, including CTA, eROSITA, the IceCube upgrade, and KM3Net, will also contribute critical scientific information on transients.

5.4 Data and high-performance computing

High-performance computing (HPC) and data management capabilities are mandatory infrastructure for astronomy. The decadal plan identifies world-class HPC and software capability for large theoretical simulations, and resources to enable processing and delivery of large data sets, as one of its five top-level science infrastructure priorities. In a community survey[7] conducted by AAL in 2019, close to half of respondents indicated that theory and/or computation play a significant role in their research activity. Access to world-class HPC is also crucial for the success of ASKAP, MWA and ultimately, SKA.

New opportunities that have arisen since the decadal plan include the funding of ADACS, which is delivered by Swinburne University of Technology, Curtin University, and the Pawsey Supercomputing Centre. ADACS fills an important place in the astronomy community by providing training and workshops for

7 https://www.surveymonkey.com/results/SM-Q8RLQ6DHV/

Professor Orsola De Marco (Macquarie University) delivers a keynote address, 'Astrophysics at the limits of HPC' at the international conference Supercomputing 2019, Denver, November 2019. CREDIT: SC19 AV TEAM

software skills, as well as merit-based software engineering support for researchers or projects. Presently ADACS is funded over a two-year cycle by AAL for $1 million per year.

The rise of gravitational wave science has seen new opportunities for funding in the HPC and data landscape. In 2019, the Gravitational Wave Data Centre was funded through AAL/NCRIS at $2.8 million over two years. This centre will be based at Swinburne University of Technology and provide dedicated infrastructure and personnel to support the hosting, real-time processing and analysis of gravitational wave data from existing and future observatories.

The astronomical community has been a leader in open data access, with most observatories hosting public archives since the 1970s, followed by the establishment of protocols and a code-base to establish virtual observatories in the 2000s. Efforts to promote open access to publications include the wide-spread use of open repositories for both data and publications. These ideas are included in the FAIR (Findable, Interoperable, Accessible, Reusable) Data Principles[8], created in 2015 to provide guidelines around best data sharing practices.

8 The FAIR data principles

Future opportunities include the establishment of:

- the Optical Data Centre, which will merge two of Australia's key optical/infrared data centres—Astronomy Data Central and the SkyMapper data portal
- the initial phase of the Australian SKA Regional Centre by ICRAR and CSIRO, which will add to existing investment in CASDA and the MWA VO data portal by providing access to post-processing, data and visualisation services for SKA pathfinders whilst building capability for the SKA.

Coordination of these data centres through common authorisation and authentication capabilities, and useful cross-platform functionality, is essential to maximise scientific returns from the substantial investments required for their development. Overall, there is a need to substantially scale up Australia's major HPC and data facilities to meet the expected significant increase in demand over the next five years.

5.5 Next-generation optical surveys

The Rubin Observatory will deliver the revolutionary Legacy Survey of Space and Time (LSST). Rubin Observatory's combination of a large collecting area (from its 8.4-m primary mirror) and massive imaging camera (3.2 Gpixel), will allow it to image the entire visible sky approximately every 3 days. The result will be an unprecedented data set of time-sensitive, deep images delivering millions of new transient sources every night. There is a substantial community of Australian astronomers engaging with this project for its ability to detect new classes of transient sources, and its ability to deliver deep, multi-colour imaging of billions of astronomical sources.

Australia's most likely means of engaging with this project will be via the provision of complementary observations and follow-up observing capabilities for the sources discovered by LSST. Australia is in the pre-eminent position to fulfill this role—its position in the southern hemisphere means that Australian facilities (including optical facilities at Siding Spring such as the Anglo-Australian Telescope, SkyMapper, the robotic ANU 2.3m, and the UK Schmidt with Taipan; and national radio facilities such as the Australia Telescope Compact Array) have unique access to observe sources in the first 8–12 hours after they are identified by the Rubin Observatory, and can monitor important variable sources when no longer visible from Chile. The power of such partnerships has already been demonstrated by the Dark Energy Survey (DES, a wide-field imaging survey based in Chile) and its collaboration with OzDES to obtain spectroscopic follow-up observations on the AAT. This path to data access highlights the clear need to retain world-class domestic optical and radio astronomy capabilities. Discussions are underway with Rubin Observatory's US consortium to identify what observing facilities, and how many nights of access, will be required to allow Australian astronomers full access to Rubin Observatory data.

Australia occupies an internationally pre-eminent position in widefield spectroscopic survey science. Key to this field are multi-fibre spectrographs, allowing astronomers to measure hundreds-to-thousands of spectra simultaneously. This is a field in which new survey capabilities are opened up by new telescopes and new instrumentation, as demonstrated by the impact of surveys from Australia's 400-fibre 2 degree Field facility on the AAT (e.g. 2dFGRS, WiggleZ, GAMA, 2dFLens, OzDES and GALAH), the UK Schmidt (e.g. 6dFGS) and international surveys such as the Sloan Digital Sky Survey (SDSS). Modest investment and the provision of front-end hardware have already permitted the participation of members of the Australian community in both the 5000-fibre Dark Energy Spectroscopic Instrument (DESI), which started observing in 2020, and the upcoming 2400-fibre 4MOST spectroscopy facility on ESO's VISTA telescope, for which Australians are leading the ground-breaking WAVES survey. Further into the future, Australia is also partnered in the Giant Magellan Telescope, for which it is building the MANIFEST fibre positioner.

The next stage of this evolution is already being planned by international teams and is likely to include dedicated 8–10-m class massively multiplexed spectroscopic facilities. The most advanced of these projects is the Maunakea Spectroscopic Explorer (MSE), with which Australian astronomers have been actively engaged over the period of the decadal plan.

MSE, however, comes at a substantial cost, and there is risk associated with the uncertain status of new construction on Maunakea Observatory. In addition to plans for MSE, ESO has long envisaged a facility of similar class. Australian engagement with these projects would require either the negotiation of full ESO membership, or continued engagement with MSE over the remainder of the decadal plan. Either route would be supported by a sizable community of Australia's optical astronomers who have a long history in widefield survey science.

Section 6:

Recommendations

6.1 Optical and infrared astronomy

6.1.1 Progress against the decadal plan

The ESO Strategic Partnership that commenced in 2017 has delivered the decadal plan's objective of access equivalent to 30% of a single 8-m telescope for the 10 years from 2017–27, as well as enabling significant new instrumentation and software contracts between ESO and the AAO Consortium for major new ESO instruments (e.g. MAVIS, 4MOST). However, this partnership with ESO is a one-off arrangement. Continued access to 8-m telescope time will critically rely on the evolution of this strategic partnership into full ESO membership for Australia.

Australia's engagement with the 25-m Giant Magellan Telescope will, when the project is completed, see the nation have access to an extremely large telescope at the 5–6% level (with the exact level of access to depend on the final cost of the telescope and Australia's level of funding for operations costs once the telescope starts doing science). The current investment by Australia (A$65 million for a US$1.99 billion telescope) will not meet the decadal plan objective of 10% of an ELT. Full membership of ESO would provide Australia with access equivalent to approximately a 7% share of the European ELT. While neither telescope alone will meet the community's decadal plan objectives, both together would.

6.1.2 The period 2020–25 and beyond

As noted above, full ESO membership will be a crucial component of Australia's astronomical portfolio going forward. It will not only address the community's long-term requirements for 8-m class telescope access, but will additionally provide access to the unique capabilities of the Atacama Large Millimeter/submillimeter Array (ALMA), and to ESO's next-generation extremely large telescope.

Gayandhi De Silva and Valentina D'Orazi commissioning the state-of-the-art HERMES instrument on the AAT at the start of the GALAH survey. The GALAH survey has since collected spectra of over half a million stars—the world's largest dataset of high resolution spectra, and aims to reach one million in total. CREDIT: KEITH SHORTRIDGE

While the current ESO Strategic Partnership will extend through the term of this decadal plan, negotiations for full ESO membership beyond the strategic partnership are expected to take several years. Australian access to the facilities of ESO in the next decadal plan will critically rely on the conclusion of negotiations with ESO before the end of this decadal plan.

Similarly, while neither GMT or the ESO ELT will become operational until well into the next decadal plan period, arrangements need to be pursued now that will ensure Australian engagement with these next-generation facilities. This will involve multiple, parallel strategies—both protecting Australia's existing investment in GMT by ensuring that the telescope is funded and completed (e.g. funding the significant GMTIFS and MANIFEST instrument projects that will be built in Australia for GMT), while also negotiating for Australian membership of ESO and resulting access to the ESO ELT.

Access to the scientific, technical and training capabilities of Australia's largest on-shore optical telescope—the 3.9-m Anglo-Australian Telescope, now funded through to 2024 by a consortium of Australian universities—remains important to the Australian astronomical community. The AAT has a long history of using innovative instrumentation to deliver internationally competitive science outcomes. The AAT's instrument suite is currently being updated using funding from multiple ARC LIEF grants. These are delivering the new Veloce high-resolution optical spectrograph for exoplanetary follow-up and the Hector multi-integral-field-spectrograph. This instrument refresh aims to keep the telescope internationally competitive in the post-2025 environment. Avenues are being actively explored to supplement these new capabilities to make the AAT attractive as a follow-up facility in the age of the Rubin Observatory.

It should be noted that full Australian membership of ESO—while the Australian astronomical community's highest optical/infrared priority—is not guaranteed. Should ESO membership not be negotiated at the end of the current strategic partnership with ESO, the AAT (and access to the GMT) will represent Australia's peak optical/infrared capabilities. In addition to looking at the purchase of 8-m class telescope time on the 'open market' at that point, Australia should also maintain the AAT as a national facility as an important risk management strategy.

There is strong support from a substantial group of Australian optical astronomers for Australian membership of Rubin Observatory's Legacy Survey of Space and Time (LSST). The most likely route for such access appears to be via the provision of in-kind services and, in particular, making time on Australia's optical and radio telescopes available to the US community for follow-up observations of LSST sources. This may well require the implementation of a new generation of instrument(s) on telescopes such as the AAT.

6.1.3 Recommendations

- Achieve full membership of the European Southern Observatory at the earliest opportunity, and certainly well before the current strategic partnership ends in 2027. This is overwhelmingly the highest optical/infrared astronomy community priority, as well as being strongly supported by Australia's millimetre/submillimetre radio community.
- Protect Australia's substantial national investment in the Giant Magellan Telescope by supporting its completion. Avenues to provide that support include the funding of GMT instrumentation projects built here in Australia, and leveraging Australian value from the substantial construction contracts being offered by the GMT.
- Explore models enabling continued access to the AAT. Models will likely require the sale or swap of telescope time, which requires processes to select (and identify funding for) new instruments that will be attractive to both potential international purchasers of AAT time, and to the members of the AAT Consortium.

- Explore paths to LSST data access from the exchange of time on Australian national facilities, including AAT time (with a suitable suite of AAT instrumentation), time on other Siding Spring Observatory telescopes, and time on national radio facilities including ASKAP, ATCA and Parkes.

6.2 Radio astronomy

6.2.1 Progress against the decadal plan

The past five years have seen substantial progress in the development and support of Australia's SKA pathfinder instruments—ASKAP and MWA. ASKAP has transitioned to operations (albeit with throughput limited by current data processing capacity), with publicly-available early science and pilot survey data leading to high-impact scientific publications. The MWA has continued to expand in both size and scientific capability, and is publishing world-leading results across its broad range of science programs. The MRO also hosts a suite of other radio facilities, including the EDGES single-element antenna that has reported the detection of the Cosmic Dawn, and SKA verification systems such as the two Engineering Development Arrays (EDA) and the Aperture Array Verification System (AAVS).

Progress toward membership, construction and scientific operations of the SKA has been excellent. Australian-based groups lead, or play a crucial role in, multiple SKA development work packages and science working groups. Establishment of the international observatory has progressed to ratification by member countries. The Australian Government has signed the SKA convention and commenced the ratification process, making a commitment for Australia to be a co-host of the observatory. The timeline for full science operations with the SKA is beyond the end of the current decadal plan period, in the late 2020s.

Domestic national facilities (including the ATCA and the Parkes 64-m telescope) continue to provide a core role in providing observational capability in the pre-SKA era, alongside ASKAP and MWA. Requests for time on these national facilities are shared by Australian-based and international researchers, supporting the philosophy of the national facility to provide capability to both domestic and international researchers. The Long Baseline Array (LBA) continues to provide high-resolution imaging capabilities, and it is important to retain unique southern hemisphere very long baseline interferometry (VLBI) capability. In addition to the national facilities, several other institution-based facilities are delivering world-leading science, notably UTMOST, which has worked with Parkes and ASKAP in the detection of fast radio bursts and other fast transients. The combined efforts

An international team from the Italian National Institute for Astrophysics and the Netherlands Institute for Radio Astronomy working with ICRAR/Curtin engineers to install antennas for the Aperture Array Verification System (AVVS) test platform. CREDIT: ICRAR/CURTIN

of these complementary facilities have propelled Australia to a world-leading role in this field. Beyond their scientific role, small to mid-scale facilities continue to play a crucial role in the training of students in observational radio astronomy, both as direct observers and through schools. These combined domestic and precursor instruments have made key advances in all of the key science questions of the decadal plan.

ATNF instrumentation has recently received a boost through two ARC LIEF grants to upgrade the ATCA's backend, and to equip the Parkes 64-m with a cryogenically-cooled phased array feed. These grants illustrate the success of collaborative programs for small- to mid-scale investments, and are evidence for Australia's continued strength in instrumentation, both radio and optical. More broadly, Australia has delivered world-class radio instrumentation domestically (e.g. the Parkes ultra-wideband receiver and the ongoing MWA upgrade) and internationally (e.g. SKA infrastructure and the critical 19-beam receiver for the Chinese Five-hundred-meter Aperture Spherical Telescope—FAST).

6.2.2 The period 2020–25 and beyond

Progress towards full science operations with the SKA remains Australia's primary goal in observational radio astronomy. The community is overwhelmingly supportive of science participation in this international project, including both the mid- and low-SKA components, but especially leveraging scientific and other benefits from the Australian-hosted component. The delay in the SKA phase 1 timeline will push the realisation of SKA science into the next decadal plan period, and place increased emphasis and pressure on existing facilities and precursors.

CSIRO Astronomy and Space Science Summer Vacation Students with staff visiting the Australia Telescope Compact Array (ATCA) in Narrabri. CREDIT: CSIRO

High-impact science is expected to be delivered from ASKAP and MWA in the period leading to the SKA, with a substantial role to be played by the combined contributions of multi-facility, multi-wavelength, and multi-messenger facilities. Maintaining and modestly enhancing capability in existing facilities will remain critical for Australia to have a strong path toward SKA, and for training the next generation of science leaders. Upgrade and expansion options for the SKA pathfinders will likely be important in the progression to SKA science.

The ATCA and Parkes will remain workhorses for the radio astronomy community over the next five years, providing an essential multi-wavelength complement to ASKAP, and supporting the growing need for radio follow-up of multi-wavelength and multi-messenger triggers from world-wide facilities. Furthermore, these facilities provide testbeds for radio astronomy instrumentation and opportunities for students to develop their skills. The availability of the ATCA and Parkes to the international community leverages access by Australian astronomers to extremely powerful international facilities such as the Jansky VLA.

Motivated by the demonstrated productivity and interactivity of current facilities, funding for upgrades will be challenged by the desire to extend the life of ageing domestic facilities. Striking a balance between the demands for funding will be served by consideration of the loss of world-leading science capabilities derived from closing or limiting facilities, and by the importance of transitioning to full SKA science.

The interconnectedness of different wavelengths will become increasingly important, as multi-messenger studies demand a range of electromagnetic follow-up. Aligned with the large radio vision of the SKA, access to large optical facilities through 8-m class telescopes, and coordination with gravitational wave facilities will be as crucial for radio-based science as the radio infrastructure itself.

Critical to the exploitation of radio data, in particular for the SKA pathfinders, is good access to HPC and data infrastructure, and good access to professional software development capability. The upgrade of national HPC infrastructure and funding of national software and data collaborations has been welcomed by the broad science community in general and the astronomy community in particular. But crucial exploitation of SKA pathfinder data requires further development of resources and infrastructure in order to deliver high-impact survey science for multiple science teams.

SKA regional centres (SRCs) will require funding in addition to SKA observatory funding. Building the expertise required to operate an effective SRC in Australia will be necessary for the Australian community to utilise SKA data in an internationally competitive manner. This process should begin in the next few years, be targeted at data from the SKA pathfinders, and be part of a national collaborative and cohesive strategy to build links and better leverage expertise in the optical, theory and gravitational wave communities. The delivery of adequate data science resources is the final critical pillar to delivering high-impact radio astronomy science over the next five years and beyond.

6.2.3 Recommendations

- Leverage Australian scientific leadership of key SKA science and facilitate returns to industry and the community through construction contracts. Construction of the SKA Observatory with its flow-on benefits is by far the highest radio astronomy priority.
- Continue to exploit MWA and ASKAP in their role as SKA pathfinders. The decade-long gap until SKA operations commence means that modest and cost-effective enhancements should be considered to maintain their scientific capability.
- Continue pursuing avenues to support domestic facilities (Parkes, ATCA, LBA), focusing on their unique observational capabilities in the pre-SKA era, and on training for students and ECRs.

CSIRO's Parkes Radio Telescope under the Milky Way. CREDIT: CSIRO

- Support development of a proto-SKA regional centre, initially to focus on the support of SKA pathfinder science, and leveraging where possible the considerable national and international supercomputing and data science resources available.

6.3 Data science and high-performance computing

6.3.1 Progress against the decadal plan

The decadal plan identified high-performance computing and data storage capabilities amongst its five top-level scientific infrastructure priorities for the coming decade. Access to world-class HPC facilities along with massive and fast data storage capabilities is critical for theory, radio, optical and gravitational wave science. For this reason Australia needs to devise a coordinated approach that will deliver the required resources commensurate with the expected growth in requirements in these various areas.

NCI and the Pawsey Supercomputing Centre hosted Australia's Tier 1 supercomputing facilities at the time of writing of the decadal plan. These machines were ageing and (particularly in the case of Pawsey) short of the required compute and storage capability for astronomy. Fortunately, federal funds have been provided over the last two years to refresh both facilities. This refresh is complete for NCI and ongoing for Pawsey. Nevertheless, the amount of time available through the National Merit Allocation Scheme and partner share options remains insufficient to meet increasingly competitive needs. This is particularly so for modern large-scale astronomical simulations, which researchers can only partly address by obtaining time with international collaborators on larger scale machines around the world. Currently about 25% of total reported usage comes from access to international HPC facilities.

The Swinburne Centre for Astrophysics and Supercomputing's OzSTAR supercomputer, partly funded by OzGrav and AAL, has helped alleviate some of the burden on the two larger-scale facilities.

Other major successes in the HPC and data landscape include the establishment of ADACS in 2017 to provide training and software development expertise; the establishment of an Australian Gravitational Wave Data Centre in 2019, and the purchase by AAL of additional supercomputing time. The creation of ADACS in particular has been strongly supported by the community, and held up as a successful model for future service delivery.

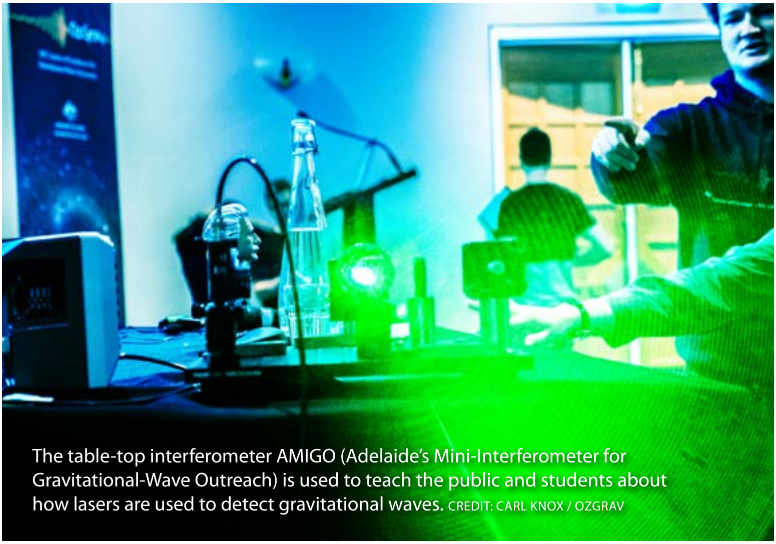
6.3.2 The period 2020–25 and beyond

Overall, considerable progress has been made relative to the decadal plan goal in this area, but new opportunities have arisen, and community expectation has grown considerably due to increasingly large and complex data sets and the requirement to provide high-resolution simulations of commensurate quality. Phase II of the NCI upgrade is nearly complete (as of early 2020), and the Pawsey upgrade is scheduled for completion in 2021. Both will provide extra capability for observational and theoretical astronomy and astrophysics. The Pawsey upgrade will provide much needed critical infrastructure for the processing of radio data of the full ASKAP surveys. Without this upgrade, ASKAP operations will remain well short of the 24/7 operations required to conclude high-impact survey science within a five-year timescale. However, the peak facilities are unlikely to fill the current shortfall being experienced by the theory community. Further access to national and international facilities will be required to alleviate some of the demand. This is not a problem that can be solved by one-off investments—a long-term, incremental plan for continuous improvement in HPC and data centres is required to keep Australian facilities at the cutting edge.

The success of ADACS in providing astronomy-focused training and support suggests that an expanded model will work for a broader community. Organisations such as ADACS and the Gravitational Wave Data Centre also provide valuable career pathways for the more technically oriented astronomers whose productivity can not be accurately captured by traditional measures such as publications.

6.3.3 Recommendations

- Support the further growth of HPC and data facilities in Australia for the astronomical sciences, but also more broadly to support the aspirations of the science community to further grow in international competitiveness.
- Establish a long-term, sustainable, distributed and interoperable set of HPC and data centre arrangements (with ongoing funding) that span the requirements of gravitational wave, radio, optical and theoretical astronomers.
- Continue funding of ADACS to provide training, professional software services and education facilities.
- Develop improved access arrangements for massive theoretical supercomputer simulations that exceed currently available Australian resources. This could include enhanced international partnerships and use of commercial cloud services to complement nationally-funded infrastructure.



The table-top interferometer AMIGO (Adelaide's Mini-Interferometer for Gravitational-Wave Outreach) is used to teach the public and students about how lasers are used to detect gravitational waves. CREDIT: CARL KNOX / OZGRAV

6.4 Gravitational waves

6.4.1 Progress against the decadal plan

Gravitational waves were on the cusp of being detected when the current decadal plan was being written and was discussed under 'mid-scale priorities'—this area of astronomy was not yet part of the core science in which Australian astronomers were involved. Since then we have seen the birth of a new field, and with that has come new opportunities and funding. The ARC Centre of Excellence for Gravitational Wave Discovery, OzGrav, was funded in 2017 to take advantage of this new discovery space, and to ensure that Australia remains a leader in pulsar timing array projects. Many members of OzGrav are also members of LIGO/Virgo and are involved directly in the detection of gravitational waves. Electromagnetic follow-up with optical and radio facilities has also played a role to unite these communities. In 2020 we can safely say that gravitational wave science has moved into the realms of astronomy, and is no longer just an experimental physics project.

6.4.2 The period 2020–25 and beyond

Upgrades to Advanced LIGO to a new facility called A+ will take place from about 2023 onwards. Through LIEF grants, Australia is contributing key A+ components and commissioning staff. The new facility should detect merging neutron stars out to three times further than Advanced LIGO, with events detected up to 10 minutes in advance of final merger. Beyond A+, the gravitational wave community is already looking to the next generation of detectors, such as the Einstein Telescope and Cosmic Explorer. While the timescale for these facilities to come online is 2030 or beyond, planning for these instruments is already underway. The Australian gravitational wave community has proposed a well-considered long-term plan for technology development and engagement with future international facilities. This includes development of a moderate-scale facility based in Australia that will pave the way for Australia to host a large international project such as Cosmic Explorer South.

In 2019, the Australian Government and AAL awarded $2.8 million over two years for the establishment of the Gravitational Wave Data Centre run by ADACS. The centre aims to process data from Advanced LIGO and from pulsar-timing array experiments. The Gravitational Wave Data Centre will be critical for gravitational wave science in Australia in the coming decade.

6.4.3 Recommendations

- Fund the design and the research and development of an Australian gravitational wave pathfinder to engage with international projects such as Cosmic Explorer and lay the foundations for a future southern hemisphere detector hosted by Australia.
- Continue funding the Gravitational Wave Data Centre, while working towards a longer-term integrated system that engages with the HPC and Data Centre requirements of the radio, optical and theory communities.

6.5 Multi-messenger—astroparticle and high energy astrophysics

6.5.1 Progress against the decadal plan

The complex energetics of many astronomical systems, such as black holes, galaxies, gamma-ray bursts and astrophysical explosions, are best understood when we can detect not only all wavelengths of light but also the high-energy particles they emit. Telescopes such as the Cherenkov Telescope Array (CTA) for studies of gamma-rays, upgrades to cosmic ray and neutrino telescopes, and Antarctic facilities, were identified in the decadal plan as priorities in this area.

As anticipated in the plan, astroparticle and high-energy astrophysics has seen a period of growth in large international facilities, in which Australian participation has been enabled by relatively modest investment. The new memorandum of understanding (MoU) between the SKA and the CTA will further foster high-level collaboration between these two major projects.

First Large-Sized-Telescope (LST) at the CTA-North site, La Palma, Spain. CREDIT: CTA

Less anticipated progress was the awarding of the ARC Centre of Excellence for Dark Matter Particle Physics, and the building of the Stawell Underground Physics Laboratory (SUPL). SUPL is a new direct dark matter detector being built in Australia, and the keystone infrastructure of the new centre of excellence.

6.5.2 The period 2020–25 and beyond

There are significant and important synergies between astroparticle physics and traditional observational astrophysics facilities from the radio to the optical. To get a complete picture of the processes operating in the Universe we need to understand the full gamut of energetic particles, and this requires enhanced collaboration between the high-energy and particle community, and the observational and theoretical astronomical community.

In coming years the astroparticle community will seek to expand involvement in the large international facilities with which they currently engage: CTA, IceCube, KM3Net and the Pierre Auger Observatory. Each of these leverages substantial international investment and enables significant Australian involvement and leadership for relatively modest cost.

Meanwhile, new opportunities have been presented by the formation of the Centre of Excellence for Dark Matter Particle Physics and SUPL. Australia has a strong theoretical and computational community in this area, in addition to the experimental physics community.

6.5.3 Recommendations

- Build on existing engagements with international projects (such as CTA and eROSITA) from which high impact outcomes can be achieved with a modest investment.
- Encourage new collaborations between astronomers and particle physicists in this emerging area, including with the Centre of Excellence for Dark Matter Particle Physics.

6.6 Space

6.6.1 Progress against the decadal plan

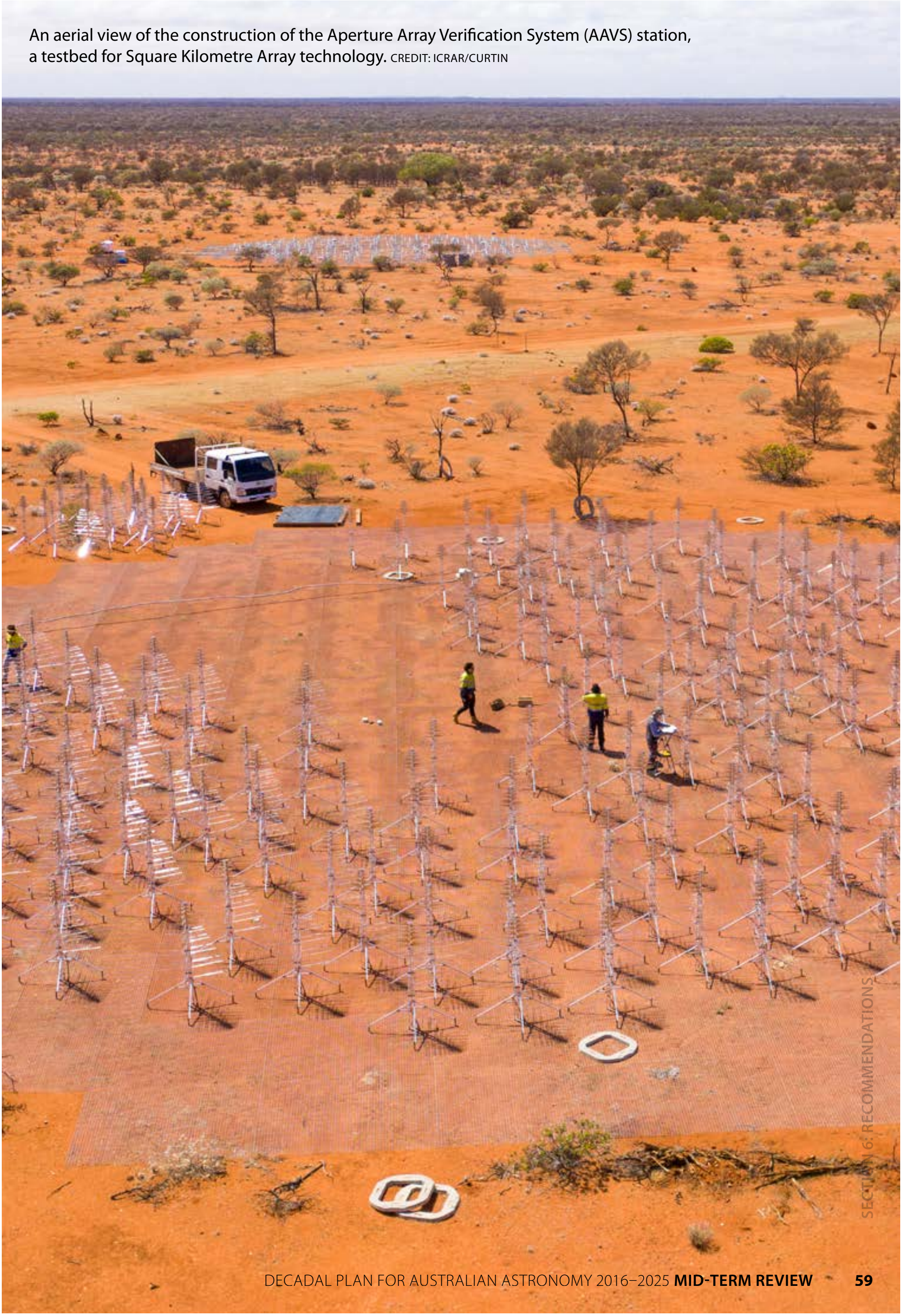
Space telescopes, unaffected by atmospheric absorption, emission or wavefront distortion, have been key drivers of scientific progress in astronomy over the last three decades. Observations from the Cosmic Background Explorer satellite and the Hubble Space Telescope led to the 2006 and 2011 Physics Nobel prizes, and future advances are becoming critically more reliant on access to space to collect data across all of the electromagnetic spectrum as an effective strategy to enable multi-messenger investigations.

The formation of a national body to coordinate engagement with space-based telescopes, as recommended in the decadal plan, has yet to be realised. The new Australian Space Agency has the potential to be a powerful entity, but currently the Australian Space Agency is essentially a separate venture from astronomy.

6.6.2 The period 2020–25 and beyond

Upcoming international flagship missions including JWST, NGRST, ATHENA and LISA, supplemented by a range of medium-scale projects such as EUCLID, PLATO and ARIEL, will contribute significant components of all the key themes in the decadal plan—ranging from the investigation of the first light sources and the Epoch of Reionisation to the discovery and characterisation of Earth-like exoplanets. These facilities will have strong synergies with ground-based observatories where there is either Australian leadership or participation, like the SKA and the GMT.

An aerial view of the construction of the Aperture Array Verification System (AAVS) station, a testbed for Square Kilometre Array technology. CREDIT: ICRAR/CURTIN



The advancement of CubeSat technology is an exciting development that is under-appreciated in the decadal plan. Traditional space telescopes have been limited to large expensive missions due to the technology required to control, point and power them, and the difficulty of downloading data from them. However, we now have the opportunity to design, build, launch and run our own Australian space telescopes.

The science cases for small space telescopes with wide fields of view and/or interferometric capabilities is strong, and the technology is now at the point where such telescopes are feasible. Australia hosts world-class instrument groups at both optical and radio frequencies, and has emerging capability in small, light, sensing and control mechanisms. With greater engagement in space-based astronomy comes the chance to apply Australian astronomical instrumentation expertise to space telescopes, contributing to nano-satellite payloads as well as larger-scale international missions.

Coordination with the new Australian Space Agency would be mutually beneficial for industry and astronomy in Australia. The astronomy research and technical community is very knowledgeable about space-related matters, including detector and communication technology, space situational awareness, imaging, data handling and analysis, and alert handling. The Australian Space Agency on the other hand has high-level contacts with industry and inter-governmental organisations.

6.6.3 Recommendations

- Explore mechanisms to build stronger ties between the Australian astronomy community, the wider Australian space science community, and the new Australian Space Agency.
- Develop capabilities in space missions through affordable small satellite technology.
- Explore arrangements that would allow Australian groups to engage with international small- to mid-scale mission opportunities (along the lines of NASA's Mission of Opportunity scheme). These could potentially leverage value from Australian strengths in instrumentation and ground station services.
- Continue to utilise Australia's global location for ground station services, where those services provide Australian scientists with access to otherwise proprietary space facilities.

6.7 Other opportunities

6.7.1 Next-generation spectroscopic survey capabilities

One of Australia's traditional strengths has been large-scale spectroscopic surveys. Australian engagement with a multiplexed spectroscopic capability on a very large telescope is important to build on this strength, but the optimum path remains unclear. For Australia to continue direct engagement with the Maunakea Spectroscopic Explorer (MSE), more funds would need to be sought. Alternatively, should Australia negotiate full membership of ESO, and if ESO commits to its own multiplexed spectroscopic capability facility, then this might address this spectroscopic survey need.

6.7.2 Antarctic astronomy

Antarctic telescope sites have demonstrated the best image quality and lowest water vapour of any site on Earth. The water vapour at Dome A is low enough to allow observations at 1.5 THz for 85 days per year, compared to five days from Chacnantor, Chile[9]. Antarctica also offers the opportunity for continuous 24-hour follow-up of transient sources, such as counterparts of gravitational wave events. Australia has a long-standing track record of site development in Antarctica, and this has allowed small instrumentation investments to leverage substantial scientific value from major new Chinese investments in instrumentation for the Dome A site. A renewed collaboration with France at Dome C is also under discussion. Australia needs to continue exploring the potential of these sites by continuing to engage with new Antarctic facilities such as the 2.5 m optical/infrared telescope KDUST, and the 5-m THz telescope DATE-5.

6.7.3 Recommendations

- Continue to explore paths for engagement with either MSE or an ESO-based equivalent facility.
- Continue to use modest instrumentation investments to engage with international projects in Antarctica, and maintain a watching brief for opportunities in THz astronomy from Antarctica as that technology improves.

6.8 Community priorities

The decadal plan's recommendations relating to community priorities remain relevant. We re-affirm these goals. However, most are still in progress (see

9 Kulesa, C.A., et al. 2013, in Astrophysics from Antarctica, Proceedings of the International Astronomical Union, IAU Symposium, Volume 288, pp. 256–263.

Section 3.2), with some having progressed more than others. There have also been a number of new community aspirations which are covered by additional recommendations.

6.8.1 Education and outreach

Astronomy has been fortunate to have a number of high-profile 'brand ambassadors', such Professor Lisa Harvey-Smith, Professor Fred Watson and Professor Alan Duffy, and many other high-profile researchers with significant outreach profiles. This has resulted in significant mainstream events and media releases which have received major public attention, and which help demonstrate the excitement of science to the younger generation. Combined with the significant community outreach and education capability present in several institutes and centres, this bodes well for the next five years when astronomers will need to continue, if not ramp up, astronomy outreach for the general public and education for school students, thereby helping to boost STEM awareness in Australia. As Section 4.3 demonstrates, the increasing prominence of astronomy in the physical sciences makes it essential to redouble efforts in this area. Several institutes have plans to improve training and mentoring for school students and develop Indigenous education and outreach schemes.

Dr Noel Nannup talks to students from Rosalie Primary School about Indigenous Astronomy.
CREDIT: ICRAR

6.8.2 Training

Training of graduates and ECRs is essential in retaining and building on Australian astronomy's world-leading research capabilities. Importantly, translation of these skills into other sectors of the economy, such as industry, defence, finance and education, is also regarded as a successful outcome by the astronomy community rather than a loss to research. Governments in particular value the contribution to a smart economy that such up-skilling provides. The recent increase in the availability of training and translation skills workshops has been welcomed by the community and has increased the number of non-academic options available for many people. It has also shown to be of benefit to government and industry, with about 30% of PhD graduates transitioning to data science roles. Better coordination of these training workshops across the community may be useful. There should also be consideration of how to further improve industry internship schemes for PhD students. Research organisations should consider becoming signatories to the Declaration on Research Assessment (DORA)[10], which promotes the development of methods of evaluating research and researchers that do not rely on traditional publication metrics. Examples relevant to astronomy include datasets, software tools and patents. This is particularly relevant for technically minded early-career astronomers for whom research publications are not a good measure of productivity.

6.8.3 Industry

Government policy towards research is gradually shifting from numerical assessment of research outputs to monitoring the engagement and impact of research with the community and with industry. As noted in sections 4.7 and 5.2, there now exist potential big-ticket opportunities for industry with respect to the SKA, ESO and space which could greatly enhance cooperation and translation of research. The astronomy community stands ready to facilitate industry engagement and be proactive in developing new opportunities with industry.

6.8.4 Gender and diversity

Several national and institutional initiatives have recently resulted in improvements in environment and culture, reduction of gender bias, and greater female participation in the workplace. There has been broad participation in the

10 DORA – San Francisco Declaration on Research Assessment (DORA)

Participants at the ICRAR-CASS Radio School 2018. CREDIT: TOBIAS WESTMEIER/ICRAR

Science in Australia Gender Equity (SAGE) initiative, co-partnered by the Australian Academy of Science and the Australian Academy of Technology and Engineering. Other initiatives include the creation of the Pleiades awards, provision of conference childcare, and the targeted hiring of female staff[11]. However, the issue of gender balance in astronomy (and STEM in general) remains concerning, and the goal of 33% female participation across all levels in astronomy is yet to be achieved. The poor retention of female ECRs is of particular concern, and the Academy's Early- and Mid-Career Researcher (EMCR) Forum is playing a role in supporting and providing advocacy for this group. Broader equity issues around sexual, cultural, religious and linguistic diversity have also become of more concern to the community, as have issues related to mental health, accessibility and prolonged periods of illness. It is therefore important that astronomy institutes continue to prioritise initiatives that address these issues, and also contribute to schemes which help the broader issue of participation in STEM studies at school. Such schemes include training for girls in schools, promoting female role models in high school science curriculums,

11 Kewley, L., 2019, Nature Astronomy, 3, 1067 increasing awareness of disparity, and increasing use of mentoring schemes for interested students.

6.7.4.1 Recommendations

- Implement institutional policies that ensure retention and recruitment targets for women in line with the recommendations of the decadal plan.
- Expand mentoring programs for young female students and family-friendly visitor programs for more senior women.
- Provide programs that promote acceptance and understanding of people from different cultural and religious backgrounds.
- Focus on the needs of people with accessibility problems, such as providing virtual access to seminars and meetings.

6.8.5 Sustainability

Although not considered in the decadal plan, much concern was expressed during mid-term review consultations with the astronomy community about astronomy's collective carbon footprint. Astronomers' individual carbon footprints are above that of the average in the wider community, mainly due to the combined effect of air travel and HPC usage. This concern resulted in mid-term review fact-finding surveys, new community committees, a new white paper, and considerable discussions on optimal ways to alter research behaviour patterns to mitigate the carbon footprint.

6.8.5.1 Recommendations

- Reduce air travel by increased use of virtual and remote conferencing capabilities, and creation of an improved remote participation experience.
- Use carbon-neutral options for conference and workshop catering and resourcing.
- Install and enable wider use of remote observing facilities. Build future facilities with remote observing, automated observing, or robotic capabilities as standard.
- Concentrate HPC usage on energy-efficient and low-carbon solutions, and invest effort, such as through ADACS services, in improving software efficiency.

The ANU SkyMapper telescope at Siding Spring Observatory, NSW. CREDIT: JAMES GILBERT

Appendix A:

Mid-term review background papers

A.1 Solicited white papers (2019)

- AAT/SSO
- Data and HPC
- ESO and ELTs (including optical instrumentation)
- Gravitational waves
- Multi-messenger/high-energy
- SKA and pathfinders (including radio instrumentation)
- Space

A.2 Facilities papers (2019)

- An Australian Space Telescope Institute and Data Centre
- Antarctic optical/IR/THz facilities and science
- Fast Radio Burst facilities and science
- Large Synoptic Survey Telescope
- Maunakea Spectroscopic Explorer
- Stawell Underground Physics Laboratory

A.3 Other papers (2020)

- Data science and astronomy: careers and pathways
- Demographics
- Diversity
- Carbon emissions in astronomy

A.4 Governance documents (2018)

- Mid-term review terms of reference
- Mid-term Review Committee conflicts register

A.5 Capabilities and opportunities documents

- Mid-term Review Capabilities and Opportunities Paper (July 2019)
- Appendix A of the above references 10 briefing documents used in the drafting of the Capabilities and Opportunities Paper, written for the National Committee for Astronomy in 2018:
  - ALMA/THz astronomy
  - Data centres
  - Education and outreach
  - Gravitational waves
  - High energy astronomy
  - Optical/infrared astronomy
  - Radio astronomy
  - Social and cultural
  - Space
  - Theory

Appendix B:

Acronyms and abbreviations

2dFGRS	2dF Galaxy Redshift Survey
2dFLens	2-degree Field Lensing Survey
4MOST	4-metre Multi-Object Spectrograph Telescope
6dFGS	6dF Galaxy Survey
A&A	Astronomy & Astrophysics
AAL	Astronomy Australia Limited
AAO	Australian Astronomical Observatory
AAT	Anglo-Australian Telescope
AAVS	Aperture Array Verification System
ADACS	Astronomy Data and Computing Services
ADS	Astrophysics Data System
AJ	Astronomical Journal
ALMA	Atacama Large Millimeter/submillimeter Array
ANITA	Australian National Institute for Theoretical Astrophysics
ANU	Australian National University
ApJ	Astrophysical Journal
ApJS	Astrophysical Journal Supplement
ARA&A	Annual Review of Astronomy and Astrophysics
ARC	Australian Research Council
ARIEL	Atmospheric Remote-sensing Infrared Exoplanet Large-survey
ASKAP	Australian SKA Pathfinder
AST	Antarctic Survey Telescopes
ASTRO 3D	ARC Centre of Excellence in All Sky Astrophysics in 3 Dimensions
ATCA	Australia Telescope Compact Array

ATHENA	Advanced Telescope for High-ENergy Astrophysics
ATNF	Australia Telescope National Facility
CAASTRO	ARC Centre of Excellence for All-sky Astrophysics
CASDA	CSIRO ASKAP Science Data Archive
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTA	Cherenkov Telescope Array
DATE-5	Dome A Terahertz Explorer
DESE	Department of Education, Skills and Employment
DESI	Dark Energy Spectroscopic Instrument
DES	Dark Energy Survey
DISER	Department of Industry, Science, Energy and Resources
DORA	Declaration on Research Assessment
ECR	Early-career researcher
EDA	Engineering Development Array
EDGES	Experiment to Detect the Global EoR Signature
ELT	Extremely large telescope
EMCR	Early- and mid-career researcher
ERA	Excellence for Research in Australia
eROSITA	Extended Roentgen Survey with an Imaging Telescope Array
ESO	European Southern Observatory
FAST	Five-hundred-meter Aperture Spherical Telescope
FAIR	Findable, Interoperable, Accessible, Reusable
FoR	Fields of Research
FRB	Fast radio burst
FTE	Full-time equivalent
GALAH	GALactic Archaeology with HERMES
GAMA	Galaxy And Mass Assembly
GDP	Gross Domestic Product
GHz	Gigahertz
GMT	Giant Magellan Telescope
GMTIFS	Giant Magellan Telescope Integral-Field Spectrograph
HERDC	Higher Education Research Data Collection

HESS	High Energy Stereoscopic System
HPC	High-performance computing
ICRAR	International Centre for Radio Astronomy Research
JWST	James Webb Space Telescope
KDUST	Kunlun Dark Universe Survey Telescope
KM3Net	Cubic Kilometre Neutrino Telescope
LBA	Long Baseline Array
LGBTQIA+	Lesbian, Gay, Bisexual, Pansexual, Transgender, Genderqueer, Queer, Intersexed, Agender, Asexual, and Ally community
LIEF	Linkage Infrastructure, Equipment and Facilities
LIGO	Laser Interferometer Gravitational-wave Observatory
LISA	Laser Interferometer Space Antenna
LOFAR	Low-Frequency Array
LSST	Legacy Survey of Space and Time
m	metre
MAGIC	Major Atmospheric Gamma Imaging Cherenkov
MANIFEST	Many Instrument Fiber System
MAVIS	MCAO-Assisted Visible Imager & Spectrograph
MHz	Megahertz
MNRAS	Monthly Notices of the Royal Astronomical Society
MoU	Memorandum of Understanding
MRO	Murchison Radio-astronomy Observatory
MSE	Maunakea Spectroscopic Explorer
MWA	Murchison Widefield Array
NASA	National Aeronautics and Space Administration
NCI	National Computational Infrastructure
NCRIS	National Collaborative Research Infrastructure Strategy
NGRST	Nancy Grace Roman Space Telescope
OzGrav	ARC Centre of Excellence for Gravitational Wave Discovery
OzSTAR	Swinburne University Supercomputer for Theoretical Astrophysics Research
pa	Per annum

PAPER	Precision Array for Probing the Epoch of Reionization
PASA	Publications of the Astronomical Society of Australia
PhD	Doctor of Philosophy
PLATO	PLATeau Observatory
QSO	Quasi-stellar object
RACS	Rapid ASKAP Continuum Survey
SAGE	Science in Australia Gender Equity
SAO	Smithsonian Astrophysical Observatory
SDSS	Sloan Digital Sky Survey
SKA	Square Kilometre Array
SRC	SKA Regional Centre
STEM	Science, technology, engineering, and mathematics
SUPL	Stawell Underground Physics Laboratory
TB	Terabyte
TESS	Transiting Exoplanet Survey Satellite
THz	Terahertz
TMT	Thirty Meter Telescope
UK	United Kingdom
US	United States
UTMOST	Molonglo Observatory Synthesis Telescope FRB upgrade
VISTA	Visible and Infrared Survey Telescope for Astronomy
VLA	Very Large Array
VLBI	Very Long Baseline Interferometry
VLT	Very Large Telescope
VO	Virtual Observatory
WAVES	Wide Area Vista Extragalactic Survey

Appendix C:

Consultation process

The Mid-term Review Committee committed to taking a consultative approach in preparing this plan. The process followed may be found in the terms of reference for the review at science.org.au/astronomy-midterm

National consultation meetings on the mid-term review:

- 14 October 2019, Swinburne University
- 15 October 2019, Monash University
- 16 October 2019, University of Melbourne
- 17 October 2019, University of Adelaide
- 24 October 2019, University of Western Australia
- 28 October 2019, Macquarie University
- 28 October 2019, Curtin University
- 31 October 2019, University of Tasmania
- 1 November 2019, University of Sydney
- 4 November 2019, Australian National University
- 12 November 2019, University of Queensland and University of Southern Queensland

Decadal plan for Australian
astronomy 2016–2025
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