Australian Academy of Science

NATIONAL COMMITTEE FOR ASTRONOMY | AUSTRALIAN ACADEMY OF SCIENCE | JULY 2015

Australia in the era of global astronomy

The decadal plan for Australian astronomy 2016–2025

Antennas of CSIRO's ASKAP radio telescope at the Murchison Radio-astronomy Observatory in Western Australia. CREDIT: A. CHERNEY/TERRASTRO.COM

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Outflows of particles (pale blue) from the Galactic Centre. The background image is the whole Milky Way at the same scale.
CREDITS: E CARRETTI, E BRESSERT (CSIRO), A MELLINGER (CENTRAL MICHIGAN UNIVERSITY)

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: Guerrilla Astronomy at the South Perth Foreshore. CREDIT K. GOTTSCHALK

Editorial note: This document is Volume I of the 2016–2025 Decadal Plan for Australian astronomy. It is the culmination of over one year's effort by the Australian astronomical community. The plan is based on the reports of 11 working groups, comprising over 150 astronomers, engineers and educators from over 30 Australian institutions across all states and the ACT. The working group reports are published electronically as part of Volume II at the following address: **www.science.org.au/astronomy-plan-2016-25**. The Decadal Plan was edited for the National Committee for Astronomy by an editorial board that included Professor Stuart Wyithe (chair), Professor Martin Asplund FAA, Dr Douglas Bock, Professor Lisa Kewley FAA and Professor Lister Staveley-Smith.

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Part of the core of the Murchison Widefield Array, the low frequency precursor for the Square Kilometre Array. The MWA was a priority of the last Decadal Plan, and was completed and brought into full science operations during the decade. CREDIT: MWA PROJECT, CURTIN UNIVERSITY

1 Executive summary

"ASTRONOMY IS ENTERING A NEW ERA OF DISCOVERY WITH GLOBAL FACILITIES"

From the birth of the first stars and galaxies to the origin of habitable planets, Australian astronomy will continue to make world-leading discoveries over the coming decade. These discoveries will be achieved through a strong platform of cutting-edge optical/infrared and radio telescopes, supported by theoretical and computational astrophysics. This Decadal Plan identifies five top-level science infrastructure priorities. These priorities are equally weighted as part of an overall astronomy capability:

- Partnership equating to 30% of an 8-metre class optical/infrared telescope;
- 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;
- Partnership equating to 10% of a 30-metre class optical/infrared extremely large telescope (ELT), such as the Giant Magellan Telescope (GMT);
- Capability within the national observatories (the Australian Astronomical Observatory, AAO; and Australia Telescope National Facility, ATNF) to maximise Australia's engagement in global projects through instrumentation development for these and other facilities;
- 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.

This Decadal Plan identifies the following four priorities for the Australian astronomy community, which augment the scientific agenda whilst also increasing its engagement, diversity and broader societal impact:

- Utilisation of astronomy to improve participation and the standard of science education in schools through teacher-training programs;
- Provision of graduate training that includes transferable skills to provide highly skilled graduates for roles in wider society;
- Establishment of a central body to promote and facilitate industry engagement with the next generation of global facilities;
- Adoption of principles and practices that aim for at least 33% female representation at all levels of Australian astronomy by 2025.

The identified priorities build on the vision outlined in *New Horizons: A Decadal Plan for Australian Astronomy, 2006–2015*. We are now entering an era where the facilities underpinning Australian astronomy will be too large for sole Australian leadership of their infrastructure. The next decade will see the major development for the international SKA. By the end of the next decade optical/infrared astronomy will see the advent of 30-metre class ELTs[1] such as the GMT. There will also be a shift in our workhorse facilities towards 8-metre class optical/infrared telescopes[2]. Continued investment for Australian capability in areas including gravitational waves, high energy, and fundamental astrophysics will leverage investment in large international projects. These areas will open new windows of discovery and provide complementary capability to core areas of Australian observational astronomy. This Decadal Plan emphasises the role of universities, which house critical skills and capabilities that are required to maintain Australia's capacity to play a leading role in the global facilities of the next decade. Australia's astronomical research excellence rests on continued partnership between astronomical observatories and the universities.

1 In this Decadal Plan, 30-metre class telescope refers to the next generation of extremely large optical/IR telescopes (ELTs) with primary apertures between 20 and 40 metres. The scaling of science capability varies with telescope radius according to the science application. The percentage recommendation simply refers to percentage of nights of a telescope of diameter greater than 20 metres.

2 In this Decadal Plan, 8-metre class telescope refers to the current generation of large optical/infrared telescopes with primary apertures between 6 and 10 metres.

"MAINTAINING A STRONG POOL OF PHD STUDENTS IS CRUCIAL FOR BUILDING THE FUTURE ASTRONOMY RESEARCH CAPACITY OF AUSTRALIA"

PhD student Lina Levin observing at the Keck Observatory. CREDIT: SWINBURNE UNIVERSITY

The past decade has seen a large rise in Australian scientific impact from international facilities. This move represents a watershed in Australian astronomical history and must be strategically managed to maintain Australia's pre-eminent role as an astronomical nation. Today, domestic national facilities, including the Anglo-Australian Telescope (AAT), the Parkes Telescope and the Australia Telescope Compact Array (ATCA) provide critical capability for Australian astronomers. This capability must be maintained during the development of the next generation of telescopes. However, resources need to be increasingly redirected to these next-generation facilities in order to answer the scientific questions posed by the Australian community. This includes redirection of funding into instrumentation development. Thus, existing telescopes may no longer be operated as national facilities at the close of this Decadal Plan period. The current roles of the AAO and the ATNF will need to grow to include oversight of Australia's partnership in international facilities coupled with instrumentation programs capable of shaping the scientific agenda for the next generation of telescopes.

Securing long-term partnership at a level equivalent to 30% of an 8-metre class telescope is necessary to answer the most fundamental science questions, and is the most pressing unresolved issue for the Australian astronomical community. Early investment in the GMT has positioned Australia to take a

The Swinburne GPU Supercomputer for Theoretical Astrophysics Research (gSTAR).
CREDIT: A. HASSAN

"ASTRONOMERS RECOGNISE THAT DATA INTENSIVE RESEARCH WILL BE AN IMPORTANT THEME IN THE NEXT DECADE AND BEYOND"

leadership role in the first of the new generation of ELTs. To capitalise on this strategic investment, Australia must also invest in partnership of 8-metre class optical/infrared telescopes to build the expertise, science foundation, and technical capacity needed to conduct world-leading ELT science and to continue Australia's leadership in instrumentation development. Options for partnership with one or more leading international observatories should be urgently explored.

The MRO in Western Australia provides a superb radio-quiet site for the SKA and its precursors, which will be the world's premier facilities at low to mid radio frequencies. ASKAP and the MWA will continue to enable ground-

breaking science as well as provide the essential research and technical expertise required for operating the SKA. The past decade has seen an increased prominence of data-intensive research across all areas of Australian astronomy. Over the next decade, astronomers will bring together data of different types and wavelengths by connecting independent data hubs. The cost of such data federation, including the HPC professionals to develop and maintain them, must be budgeted for when projects are being planned.

The engagement of industry will become increasingly important in the coming decade as the focus of the scientific community moves from local facilities, which have often been designed and built domestically, towards new mega-projects. This Decadal Plan recommends establishing a program for astronomy–industry development, to support and facilitate strategic academic–industry collaborations, and increasing mobility of personnel.

Astronomy is a successful vehicle for promoting engagement with, and attracting students into the science, technology, engineering and mathematics (STEM) disciplines. The community should continue to use astronomy to help improve the standard of science education in schools through teacher-training programs. Training aimed at improving the 'transferrable' skills of our graduate and postgraduate students will also help Australia improve its STEM capacity, and provide highly valued graduates for roles in wider society.

The professional Australian astronomy community has undergone significant growth in the past decade with a rise in research capacity across the entire community, particularly in the training of higher-degree students and early-career researchers. However, Australian astronomy must address the low level of female participation amongst its workforce, which has remained at 20% over the past decade. The community should aim for at least 33% participation at all levels by 2025. This goal is aligned with the demographics of the Australian astronomy PhD student cohort at the start of this decadal planning period.

Theoretical and computational astrophysics has grown to become a focus across all areas of strength in Australian astronomy research, now representing approximately one-third of its research impact. Alongside the growing need for HPC to process data products from the next generation of telescopes, computational astrophysics in Australia will also require strategic HPC investment. The estimated HPC resource needed for Australian astronomy

The Australian Gemini Astronomy Contests 2013's winning image proposed by contest winner, Isobelle Teljega, in year 8 of St Margaret's Anglican School. Within the spiral galaxy IC5332, magenta 'bubbles' show small bursts of new star formation. CREDIT: AAO

to achieve these goals corresponds to approximately the equivalent of 30% of a top-100 supercomputer.

Total funding levels during the past decade have met those envisaged in the last Decadal Plan, enabling achievement of most of that plan's recommendations. The clear exception is the case of 8-metre class optical/infrared telescope access where unpredictable funding profiles and timescales have meant that the targets set at the start of the period covered by the last Decadal Plan have not been consolidated. With the increasingly international focus of large-scale astronomy infrastructure, this Decadal Plan highlights the fundamental importance of a stable, predictable, system for funding major research infrastructure. In addition to facilitating effective engagement with large-scale international projects, a strategic approach to funding should be flexible enough to provide opportunities for mid-scale investments in initiatives such as development of an 8-metre class optical/infrared wide-field spectroscopic survey telescope, or in emerging areas of Australian astronomy such as high energy astrophysics (including cosmic rays, gamma rays and neutrinos) and gravitational waves.

While a decade is an appropriate timescale on which to revisit strategic planning across the community, the vision outlined in *New Horizons: The Decadal Plan for Australian Astronomy 2006–2015* looked beyond the past

decade, recommending far-reaching investments in multi-decade global projects such as the GMT and the SKA. These recent long-term investments will come to fruition in the coming decade, providing key opportunities for innovation and industry partnerships, and positioning Australia to continue as a global astronomy leader in the future. For these reasons, we have titled this Decadal Plan for Australian astronomy 2016–2025, *Australia in the Era of Global Astronomy*. The era of global astronomy facilities and discoveries has begun.

A Halls Creek student's reaction to seeing the Sun through a telescope for the first time. CREDIT: ICRAR

2 Audience and intent

“AUSTRALIAN ASTRONOMERS SPEAK WITH ONE VOICE THROUGH THIS DECADAL PLAN”

This report, *Australia in the Era of Global Astronomy*, contains the strategic vision for Australian astronomy in the decade 2016–2025. It follows from *New Horizons: A Decadal Plan for Australian Astronomy 2006–2015* and the subsequent *mid-term review*.

The outcomes and recommendations in this report are aimed at informing the primary stakeholders of Australian astronomy of the current status of the field, the strengths and progress made by the Australian astronomy community, the big scientific questions that Australia is best equipped to answer, and the infrastructure and capability priorities for the future needed to realise this ambition.

Stakeholders include Australian governments at federal and state levels, which provide the greatest source of funding that enables scientific research through agencies including the Australian Research Council (ARC), as well as Australia's universities, which provide the greatest pool of Australia's research capability and training. The Australian Astronomical Observatory (AAO) and CSIRO Astronomy and Space Science, which both conduct astronomical research and facilitate access for Australian astronomers to world-class telescopes, have a special role within Australian astronomy. This Decadal Plan makes recommendations on important issues in areas of education, training and careers at all levels that are critical to maintain Australia's position as a forefront research nation. Not all recommendations in this area are unique to astronomy.

The Australian astronomical community has worked collectively to develop this Decadal Plan. The findings and recommendations reported have been

"GREATER COLLABORATION AND PARTNERSHIP AMONG RESEARCH ORGANISATIONS AND OUTREACH PROVIDERS IS ESSENTIAL FOR EXPANDING THE PUBLIC IMPACT OF ASTRONOMY"

drawn from the conclusions of eleven working groups formed to consider the issues facing Australian astronomy across all areas including science, education and capability. Membership of these working groups spanned all institutions with active astronomy research and/or teaching programs. The detailed reports are available as a second volume in electronic form. The working group reports will serve as a valuable internal reference, as the community seeks to identify the specific scientific questions to be pursued and works to develop detailed implementation plans in line with the recommendations of this Decadal Plan.

3 Update: A decade of achievement

"Australian astronomers make discoveries at the frontier of knowledge"

Over the past decade, Australian astronomers have achieved major international breakthroughs in optical/infrared (optical/IR) and radio astronomy and in theoretical astrophysics. Australian astronomers precisely measured the properties of stars, galaxies and of the Universe, significantly advancing our understanding of the cosmos. On the largest scales, the mass, geometry, and expansion of the Universe have been measured to exquisite accuracy using giant surveys of galaxies and exploding stars, and by probing the cosmic microwave background. Planetary astronomy has undergone a revolution, with the number of planets discovered around other stars now counted in the thousands.

Australian cosmologists established the technique of making simultaneous measurements of the expansion and growth history of the Universe, by measuring fluctuations in its density and distortions in its shape. Surveys at optical/IR and radio wavelengths have expanded our understanding of how galaxies formed. Pioneering instrumentation at the Anglo-Australian Telescope (AAT) has allowed the use of stellar motions to measure the build-up of rotation in distant galaxies, showing that turbulence is driven by star formation and not cosmic accretion as previously thought.

The past decade has seen significant leadership from Australian astronomers in uncovering the life story of the Milky Way using the chemistry and motions of stars, a technique termed 'galactic archaeology'. Our understanding of the earliest epochs of the Milky Way and the nature of the first stars has progressed significantly over the past decade, with Australian astronomers discovering the majority of the most chemically pristine and thus oldest stars known.

The celebrated double pulsar that led to the most accurate confirmation of Einstein's theory of general relativity was discovered with the Parkes telescope. The last decade has seen the extensive use of pulsars to place limits on ripples in space–time by gravitational waves and probe the collisions of the largest black holes in the early Universe. New techniques in radio observation have been used to untangle the large-scale structure of the magnetic field in the Milky Way and the neighbouring Magellanic Clouds.

These are just a few areas in which Australian astronomers have made pivotal discoveries, advancing understanding of key questions posed in the previous Decadal Plan. Bolstered by these successes, Australian astronomy enjoys an international reputation for innovation and scientific achievement, as evidenced by the 2013 document[1] 'Benchmarking Australian Science Performance' which demonstrates that astronomy is Australia's leading physics discipline in terms of relative citation rate, and one of only two physics disciplines that performs above the European standard.

The significant scientific achievements outlined above tell only part of the success story of Australian astronomy over the past decade. Australia has been laying the groundwork for the international Square Kilometre Array (SKA) and Giant Magellan Telescope (GMT) projects—both of which will herald a new era of discovery. SKA successes include developing the world's most radio-quiet observatory site, which was a key factor in the decision to site SKA components in Western Australia, and the novel *phased array feed* radio receiving systems for the Australian SKA Pathfinder (ASKAP). Completion of the Murchison Widefield Array (MWA) provided the basis for the low-frequency component of the SKA. The construction go-ahead for the GMT, and the selection of the Australian-led GMT Integral Field Spectrometer (GMTIFS) and MANIFEST instruments represent critical milestones for the future of Australian optical/IR astronomy. These major achievements highlight the rapidly increasing globalisation in Australian astronomy.

1 www.chiefscientist.gov.au/2013/02/benchmarking-australian-science-performance/

The 2011 Nobel Prize in Physics: 100 years in the making

In 2011, cosmologist Professor Brian Schmidt of the Australian National University became the first Australian in 96 years to be awarded a Nobel Prize in Physics.

This prize represents a century of Australian investment in astronomy, starting in 1911 with the establishment of the Oddie telescope on Mount Stromlo. By 1927 Mount Stromlo was the premier observatory in Australia, and was expanded in the 1940s and 1950s by Sir Richard Woolley. During this period, what is now called CSIRO and The University of Sydney established a world-leading radio astronomy program that led to the Parkes telescope, finished in 1961. To complement this facility, Australia needed a large optical telescope, and the 3.9-metre Anglo-Australian Telescope (AAT) was completed in 1974.

Through the attraction of preeminent astronomers to use these world-class facilities, Australia was able to advance our understanding of cosmology. The Parkes telescope helped discover quasars by precisely locating the first of these radio objects in 1962. In 1970, using optical and radio data, Ken Freeman showed for the first time that galaxies appeared to have large quantities of dark matter. Through the 1980s and 1990s Australia built up a unique technology that allowed the AAT to undertake large surveys of galaxies, such as the celebrated 2dF redshift survey led by Matthew Colless.

In 1993, Jeremy Mould became director of Mount Stromlo Observatory, and undertook his program to measure the expansion rate of the Universe with the Hubble Space Telescope. In 1994, he recruited Brian Schmidt to undertake his team's experiment to measure the change in the rate of the expansion of the Universe using exploding stars. This experiment, along with work by a US-based team in 1998, made the unexpected discovery that the expansion of the Universe appeared to be accelerating. The US-based team led by Saul Perlmutter also made its first observations on the AAT, in collaboration with Brian Boyle and Warrick Couch.

Before this result could be accepted, confirmation needed to be gained through additional experiments including measurements of the cosmic microwave background, the Australian co-led Hubble Constant measurement, and a series of Australian-led measurements of the large-scale structure of galaxies.

These experiments form the basis of the Standard Model of Cosmology—an incredibly successful description of our Universe—the development of which Australia can be justifiably proud in taking a leading role.

Brian Schmidt receiving his Nobel Prize diploma and medal from His Majesty the King of Sweden in 2011

Recognition of excellence

Since publication of the previous decadal plan, Australian astronomers have continued to have impressive success with national and international prizes for science. Like the Nobel Prize in 2011, this success is built on substantial investment in people and infrastructure over a sustained period of time. The following provide a selection of examples:

The international **Gruber Prize in Cosmology** is awarded annually for theoretical, analytical, conceptual or observational discoveries leading to fundamental advances in understanding our Universe.

- In 2014, Professor Ken Freeman of the Australian National University shared the award with Jaan Einasto, R Brent Tully, and Sidney van den Bergh for their observations and analyses of the structure and evolution of the nearby Universe; laying the foundations of Near Field Cosmology.

- In 2009, Professor Jeremy Mould now at Swinburne University of Technology was awarded the prize along with Wendy Freedman and Robert Kennicutt for the definitive measurement of the Hubble Constant, the rate of expansion of the Universe, which effectively connects the Universe's age to its size.
- In 2007, Professor Brian Schmidt of the Australian National University and the High-Z Supernova Search Team shared the prize with Saul Perlmutter and the Supernova Cosmology Project Team for their discovery that the expansion of the Universe is accelerating.

The **Prime Minister's Prize for Science** is Australia's pre-eminent award for excellence and a tribute to the contribution of Australian scientists to the economic and social well-being of the country and the world.

- 2012 recipient Professor Ken Freeman of the Australian National University received the prize for his foundational work determining the age and movement of stars in our own galaxy.
- 2009 recipient Dr John O'Sullivan of CSIRO was honoured for achievement in astronomy and wireless technologies.

The **Australian Academy of Science's Matthew Flinders Medal and Lecture** is awarded for scientific research of the highest standing in the physical sciences.

- In 2013, Professor Ken Freeman of the Australian National University was honoured for identifying the necessity for dark matter, and for his role in shaping our current understanding of the dynamics and structure of galaxies.

The Australian **Malcolm McIntosh Prize for Physical Scientist of the Year** is awarded to early or mid-career researchers in recognition of an outstanding achievement in science that advances or has the potential to advance, human welfare or benefits society.

- Professor Stuart Wyithe from The University of Melbourne received the prize in 2011 for his work on the physics of the formation of the Universe.
- CSIRO's Dr Naomi McClure-Griffiths was awarded the prize in 2006 for her insight into the structure of our galaxy and her research leadership.

The **Australian Academy of Science's Nancy Millis Medal** recognises outstanding research by female scientists between 8 and 15 years post-PhD in any branch of natural science.

- 2015 recipient Professor Tamara Davis from The University of Queensland was awarded the medal for her work testing our fundamental laws of physics, and studies of the nature of dark energy and dark matter.

The **Australian Academy of Science's Pawsey Medal** recognises outstanding research in physics by scientists up to 15 years post-PhD.

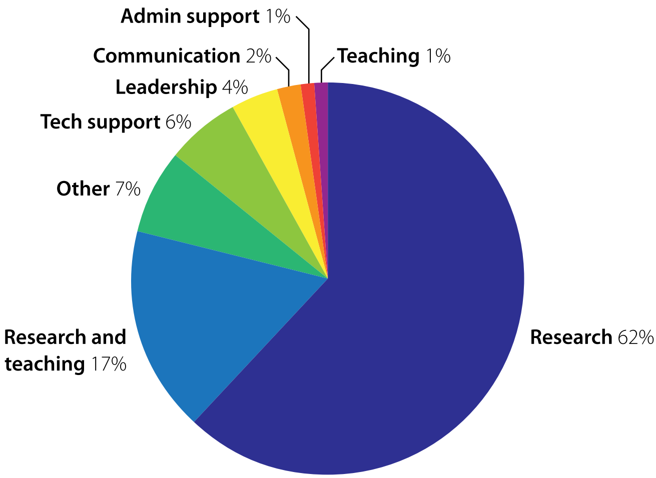
- 2015 recipient Professor Naomi McClure-Griffiths of the Australian National University was awarded the medal for her insights into how the Milky Way is structured, lives its life, and interacts with its neighbours.
- 2013 recipient Associate Professor Christopher Blake of Swinburne University of Technology received the medal for his work creating and using maps of how galaxies are scattered through space to help understand the Universe's accelerating expansion.
- 2011 recipient Professor Bryan Gaensler from The University of Sydney, was recognised for his pioneering studies of cosmic magnetism using detailed three-dimensional maps of large-scale magnetic fields throughout the cosmos.
- 2009 recipient Dr Stuart Wyithe of The University of Melbourne, was honoured for his work developing clear predictions of expected observational signatures for the processes leading to black holes, stars and galaxies.

4 Snapshot: Australian astronomy 2015

"AUSTRALIAN ASTRONOMY HAS ENJOYED A DECADE OF GROWTH AND ACHIEVEMENT"

The past decade has seen significant growth (25%) of the Australian professional astronomical community[1] as well as geographic diversification, particularly to Western Australia. The Australian professional astronomy community numbered 527 full-time equivalents (FTEs) in January 2014. During the past five years, there have been 312 new appointments in astronomy

Figure 4.1: Graphical summary of the primary roles of Australian astronomers according to the survey data gathered in 2014



1 Excluding PhD students. Demographic data is based on analysis presented in the WG3.1 report.

Preparing the the Sydney-Australian-Astronomical-Observatory Multi-object Integral-Field Spectrograph (SAMI) for observations on the AAT. SAMI allows a unique view of stars and gas inside distant galaxies by enabling collection of dozens of spectra across the entire face of each galaxy.
CREDIT: A. BAUER (AAO)

"AUSTRALIAN ASTRONOMY MUST ADDRESS THE LOW LEVEL OF FEMALE PARTICIPATION AMONG ITS WORKFORCE"

together with 169 departures. Most community growth has occurred in research capability, which numbered 349 FTE in 2014. The largest number of new appointments occurred in 2011, which coincided with significant injections of competitive federal funding via ARC Centre of Excellence and Super Science programs. The number of continuing staff involved in astronomy research, who are critical for the ongoing scientific coherence and productivity of the community, increased from 107 to 139. In the past decade, 60% of new appointments were made from overseas, leading to a net gain of astronomy expertise to Australia. Figure 4.1 illustrates the distribution of roles undertaken by Australian astronomers. The dominant role is in research, reflecting the need to invest in people to capitalise on new research facilities.

There has been no change in the percentage of women in Australian astronomy over the past decade, with representation constant at 20% across the astronomical community as a whole. However, the percentage of women in continuing positions has nearly doubled from 10% to 19%. Similar trends were seen overseas over the same period.

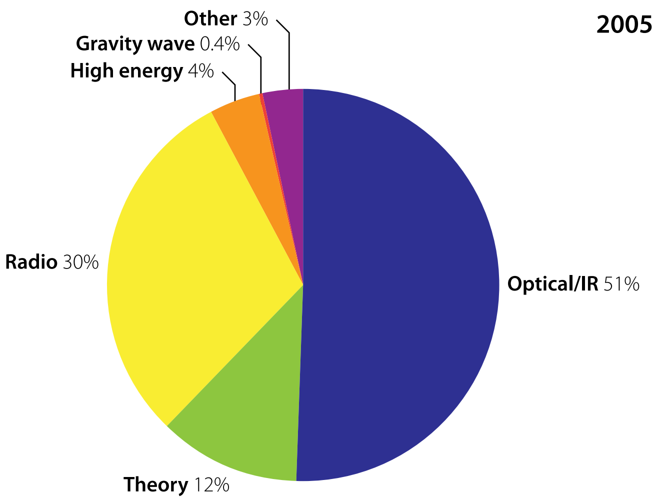
4.1 Australian astronomy research

The scientific impact of Australian astronomical research[2] is dominated by theoretical and computational astrophysics, and by observational astronomy using optical/IR and radio telescopes. Figure 4.2 shows that together these amount to more than 90% of all Australian impact-weighted activity[3]. While

2 Bibliometric data is based on analysis presented in the Australian Astronomy Publication and Facilities Survey, September 2014.

3 Scientific impact is defined as the citations to a paper normalised by the fraction of authorship by astronomers resident in Australia during 2014, and by the average citations to all astronomy papers in the year of publication.

Figure 4.2: Graphical summary of the citation-weighted impact of different techniques in Australian astronomy in the decade to 2014 (bottom), showing the relative changes since 2005 (top). Optical/IR refers to use of the combination of ground-based optical/IR, and space-based optical/IR and UV facilities



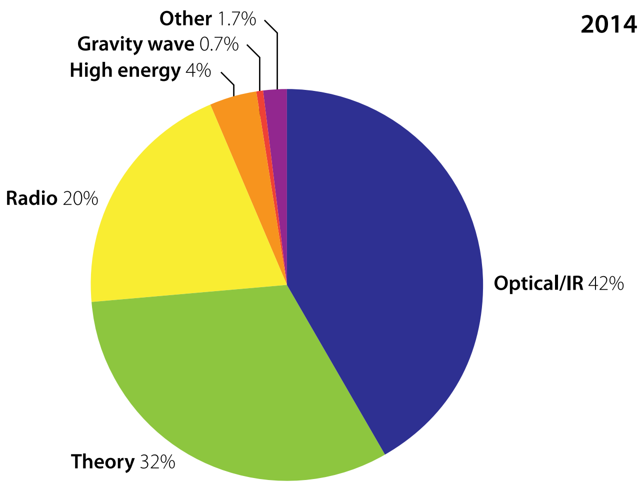
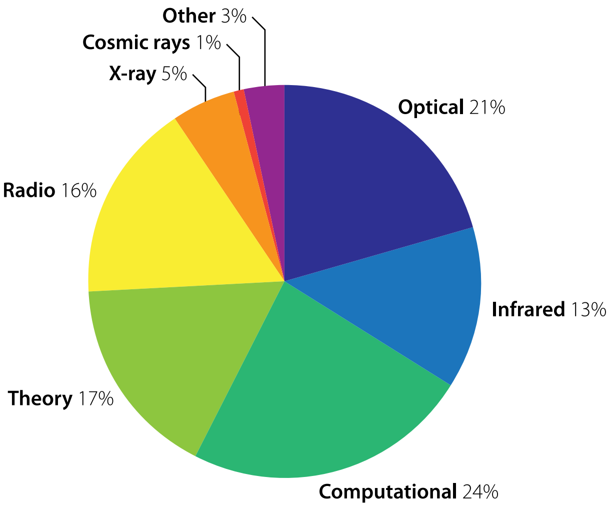


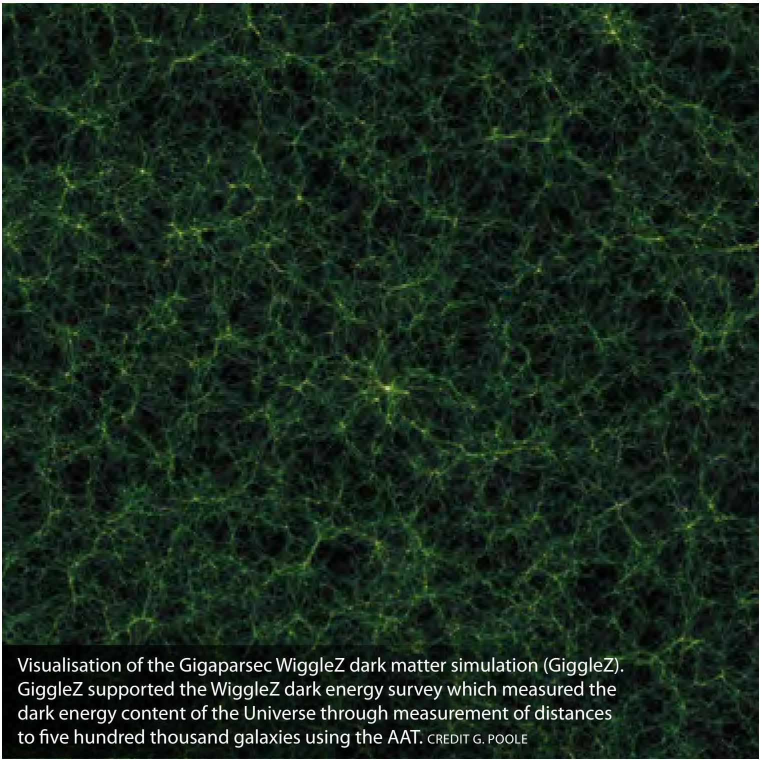
Figure 4.3: Techniques used by Australian astronomers, expressed as the percentage of researcher effort. Many individual astronomers contribute across multiple techniques. The wedge labelled 'Other' includes astronomical areas not elsewhere listed



absolute output from the community has increased substantially in all areas of astronomy, the largest single change has been the tripling of participation and scientific impact in astrophysical theory. Indeed, theory (which includes analytic theory and computer modelling of astrophysical processes and observations) has established itself as a major contributor to Australian astronomical research activity, rising from ~10% of impact-weighted activity in 2005, to ~30% of activity in 2014. Optical/IR and radio astronomy observational research have grown less rapidly, with current levels of about 40% and 20% of total research output, respectively[4]. The impact-weighted activity in high-energy astrophysics has been steady at ~4% over the past decade.

The same trend of more rapid growth in theoretical and computational research is also seen among the research FTE being invested in these areas. As of January 2014, 41% of the effort contributed by Australian astronomical researchers is identified with theoretical or computational astrophysics, 34%

4 Observational research output in the coming decade can be expected to grow rapidly with the recent investment in new infrastructure, especially at radio wavelengths.



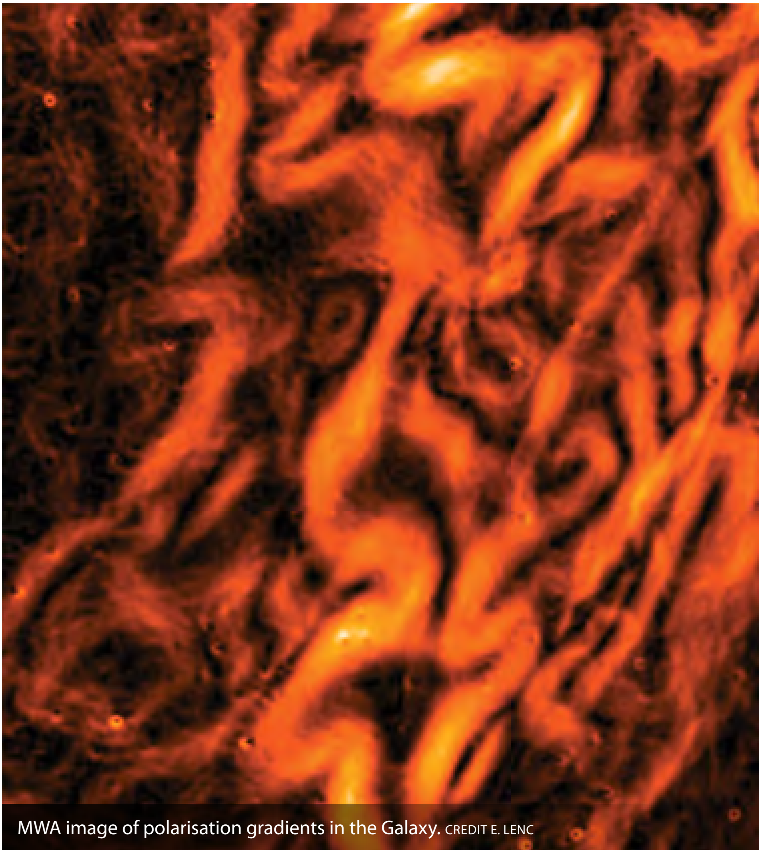
Visualisation of the Gigaparsec WiggleZ dark matter simulation (GiggleZ). GiggleZ supported the WiggleZ dark energy survey which measured the dark energy content of the Universe through measurement of distances to five hundred thousand galaxies using the AAT. CREDIT G. POOLE

with optical/IR astronomy, 16% with radio astronomy, and 5% in areas of X-ray or cosmic-ray astronomy[5] (Figure 4.3). We stress that individual astronomers contribute across multiple areas shown in Figure 4.3. Indeed more than a quarter of the papers published over the past decade involved two or more of optical/IR astronomy, radio astronomy, and theoretical astronomy.

> **"THE MASS, GEOMETRY, AND EXPANSION OF THE UNIVERSE HAVE BEEN MEASURED TO EXQUISITE ACCURACY"**

Within radio astronomy, approximately two-thirds of impact-weighted activity utilises Australian-based radio telescopes with approximately 30% each attributed to the Australia Telescope Compact Array and the Parkes telescope.

5 Based on data presented in the WG3.1 report.


MWA image of polarisation gradients in the Galaxy. CREDIT E. LENC

The remaining one-third of impact-weighted activity is now based on the use of overseas facilities, double the corresponding use during the past Decadal Plan period. Within optical/IR astronomy, use of overseas facilities now represents two-thirds of the output of current research, compared to less than half prior to 2005. In addition to international 8-metre class optical/IR telescopes, the main growth area has been in the use of space-based facilities, which now accounts for 30% of optical/IR citation impact-weighted activity. Thus, the past decade has seen growth in scientific impact through the use of overseas facilities, reflecting the increasing globalisation of astronomy.

4.2 Australian astronomy capability and funding

The funding targets set out in the previous Decadal Plan were ambitious but considered achievable. Together with re-prioritisation, these targets were perceived as required to maintain Australia's position in international astronomy. Many funding targets from the last Decadal Plan have been met or exceeded, with significant investments in radio and optical/IR astronomical infrastructure. This includes the major projects of ASKAP and the GMT, as well as ongoing upgrades and instrumentation developments at Australia's national telescopes. The major unmet target from the last Decadal Plan is national ongoing partnership in the equivalent of 20% of an 8-metre class optical/IR telescope.

The Skymapper telescope. SkyMapper is a state-of-the-art automated wide-field survey telescope which is creating the first comprehensive digital survey of the entire southern sky. CREDIT: ANU

The previous Decadal Plan foresaw that funding for new radio astronomy facilities supporting development of the SKA would reach a level of \$10M per annum (p.a.) by 2015. New investments in ASKAP and MWA as well as pre-construction funds for the development of SKA Phase-I at a level of approximately \$18M p.a. have exceeded this goal. This investment has secured Australia as a host country for the multi-billion dollar SKA project and has seeded numerous industry partnerships. Continued investment and partnership in the SKA remains one of the top two new facility priorities for the Australian community to maintain Australia's position at the forefront of international astronomy.

"ASTRONOMERS WILL BRING TOGETHER DATA OF DIFFERENT TYPES AND WAVELENGTHS BY CONNECTING INDEPENDENT DATA HUBS"

The previous Decadal Plan also indicated that providing capability necessary for Australian astronomers to achieve their scientific ambition would require funding of about \$7.5M p.a. for new optical/IR facilities. New funding for the GMT partnership and for access to the Magellan telescopes together average to slightly more than \$8M p.a., reaching the level targeted by the previous

School students experiencing a 3D AstroTour at the Swinburne Virtual Reality Theatre. Approximately 25,000 people, including schools and the public, have experienced an AstroTour. CREDIT SWINBURNE UNIVERSITY OF TECHNOLOGY

"OVER THE PAST FIVE YEARS, THERE HAVE BEEN OVER 7,800 ASTRONOMY OUTREACH ACTIVITIES ACROSS AUSTRALIA ATTENDED BY OVER 1.34 MILLION PEOPLE"

Decadal Plan, albeit with a different distribution of funding between 30-metre class (i.e. ELT) and 8-metre class telescope access than that foreseen. However, Australian access to operational state-of-the-art optical/IR telescopes is now at a critically low level. The extent of the challenge facing Australian optical/IR astronomy to remain internationally competitive is illustrated by the fact that Australia's fraction[6] of the world's optical/IR telescope collecting area has dropped from 7.5% at the time the AAT was commissioned in 1974 to 1.5% today.

6 Fraction of world telescope collecting area (for scientific telescopes over 2 metres in size).

Australia has been fortunate to have its major domestic astronomical facilities at optical/IR and radio wavelengths operated by a pair of efficient and internationally highly regarded organisations in the Australian Astronomical Observatory (AAO; currently part of the Department of Industry and Science) and CSIRO Astronomy and Space Science (which operates the ATNF). Together these organisations receive significant federal direct funding at a level of $11M p.a. for AAO and $19M p.a. for the ATNF, to operate key facilities available to all Australian researchers as well as to employ researchers and support staff. In addition, both organisations win contracts to carry out instrumentation development, operations and research support.

Funding goals from the last Decadal Plan included a doubling of National Competitive Grant Program (NCGP) income, a goal that has been largely met. Australian astronomy's NCGP[7] income has risen by ~90% to $18.8M in 2014[8]. This growth has mainly arisen from a larger available NCGP, although Australian astronomy has also increased its share of this funding pool by approximately 14%. The formation of the ARC Centre of Excellence for All-Sky Astrophysics (CAASTRO) accounts for essentially all of this growth. The improvements in Australia's astronomical research capability have been both driven by, and facilitated by, this increase in grant funding.

The federal government supports overheads associated with research (e.g. research facilities, buildings, electricity, libraries) through a variety of block grant schemes to universities. Some of this funding supports astronomical facilities such as the Australian National University (ANU) operating the Siding Spring Observatory, and ANU and Swinburne University of Technology purchasing a modest additional amount of observing time on the Keck telescopes. The block grants also support Australian and international Higher Degree Research students. Further funding for astronomy comes from state governments, most notably in Western Australia where the International Centre for Radio Astronomy Research (ICRAR) has been supported at the level of $46M over the period 2009 to 2019.

7 In this Decadal Plan we list costs in 2015 dollars.

8 For comparison the consumer price index has grown ~30% over the same period.

Revolution in asteroseismology

The past decade has seen a revolution in the field of asteroseismology—a stellar analogy to using earthquakes to study the Earth's interior. Through exquisite measurements of soundwaves inside stars astronomers can probe the fundamental properties of stars in detail. This elegant concept is similar to inferring the type of instruments in a symphony orchestra from the sound they each produce.

The current transformation in this field has been enabled by ambitious European Space Agency (ESA) and National Aeronautics and Space Administration (NASA) space telescopes built to measure the brightness of stars over very long times. The ultra-high precision data can both show the signatures of orbiting planets as they move across the disk of their host star and detect brightness variations caused by oscillating soundwaves inside the star.

Expertise in asteroseismology by Australian astronomers has leveraged strong collaboration with NASA to work on data from its ground-breaking Kepler mission. Kepler-related research has resulted in a dramatic boost of high-impact papers from the Australian astronomical community. Among the researchers is Dr Dennis Stello (an ARC Future Fellow at The University of Sydney) who has helped NASA determine the fundamental properties of the planetary systems found by Kepler. Of particular significance was the detection of planet Kepler 22b for which Dr Stello used asteroseismic techniques to determine the size, mass and age of its host star; the asteroseismic results underpinned the discovery that Kepler 22b was an Earth-sized planet in the habitable zone around a Sun-like star.

The successes of previous missions have led NASA and ESA to fund next-generation space telescopes for the coming decade and beyond including K2, TESS, and PLATO that will observe millions of stars across the galaxy, and Australian astronomers are already involved in all three missions. Aiming also at the southern sky, these missions provide unique opportunities for Australian astronomers across different lines of research—including stellar astrophysics, planet detection and galaxy structure and evolution—to participate at a much greater level than in the past.

Expertise and capabilities of the Australian astronomical community and facilities such as the HERMES spectrograph on the AAT will be crucial to fully exploit the rich space-based data, leveraging strong national and international collaboration in the next decade, which promises to be truly spectacular.

5 Education: The foundation of astronomy

"OUR FUTURE RESTS ON INSPIRING AND TRAINING A NEW GENERATION OF SCIENTISTS AND CITIZENS"

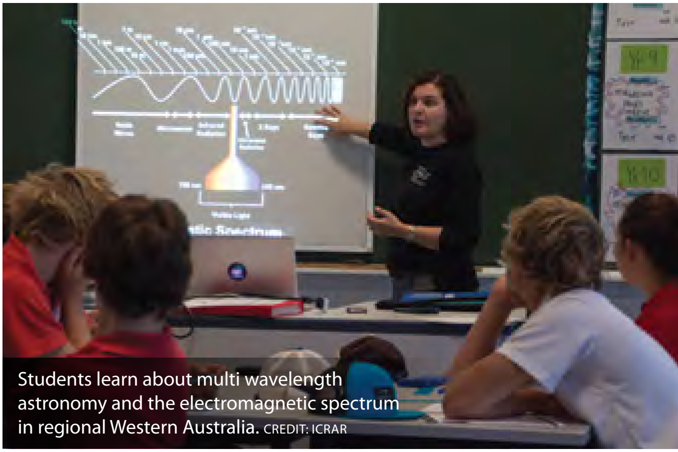
Communicating astronomical discoveries and achievements to the broadest possible audience is crucial for engaging the general public in astronomy and inspiring students to consider a career in science, technology, engineering and mathematics (STEM) research areas. Attracting STEM students into astronomy and training them for large-scale use of the next generation of facilities is critical for maintaining Australian leadership on the international stage.

Public outreach by universities and professional astronomy organisations as well as by museums, planetaria, and public observatories has a long-lasting impact on the engagement of the general public with astronomy, and on attracting primary and high school students to science. Over the past five years, there have been over 7,800 astronomy outreach activities across Australia attended by over 1.34 million people[1]. In the next decade, greater collaboration and partnership among astronomy research organisations and astronomy outreach providers is essential for expanding the public impact of astronomy. An organisation such as the Astronomical Society of Australia's Education and Public Outreach Chapter (EPOC) could initiate and facilitate these interactions, as well as provide a central point of contact for astronomers to liaise with state and national education providers for the development of astronomy curriculum materials and initiatives.

Attracting students into astronomy requires more interaction between professional astronomers and education providers. Teacher-training programs, including high-quality astronomy teaching materials, can significantly impact

1 Figures based on analysis presented in the WG3.2 report.

"ASTRONOMY IS A SUCCESSFUL VEHICLE FOR ATTRACTING STUDENTS INTO THE STEM DISCIPLINES"


Students learn about multi wavelength astronomy and the electromagnetic spectrum in regional Western Australia. CREDIT: ICRAR

the quality of school education. Over the past five years, 3,300 teachers have attended teacher-training programs offered by Australian astronomical education and outreach institutions. There remains a significant need and opportunity for effective training of teachers and for implementation of effective astronomy materials within the new Australian F–10 Science Curriculum. Engagement of astronomers in teacher-training programs and curriculum development at the primary and secondary levels is recommended as the highest priority in this area.

Maintaining a strong pool of PhD students is crucial for building the future astronomy research capacity of Australia. The cohort of Australian astronomy PhD students has grown by 70% over the past decade[2]. In 2014, a total of 266 PhD students were enrolled in astronomy programs nationwide, compared with 157 PhD students enrolled in 2005. This rise in astronomy PhD student enrolments corresponds to a similar rise in PhD graduates; a total of 184 PhD students graduated between 2009 and 2014 compared with 84 PhD graduates between 1999 and 2004. In 2014, half of astronomy PhD applications and one-third of PhD commencements were from overseas, a trend that is in keeping with the increasing globalisation of astronomical research. However, among Australian students there is little institutional mobility between Honours and PhD studies, which limits their opportunities and experience. Of the 71% of Honours graduates who continued into PhD programs, only 11% changed institution for their PhD. This lack of mobility between undergraduate

2 Based on analysis presented in the WG3.1 report.

and PhD institutions is in contrast to educational institutions overseas, such as in the USA and Europe, where the majority of students move to other states or countries to undertake PhD studies.

The fraction of female astronomy PhD graduates has fallen slightly across the decade, from 37% graduating between 2000 and 2004 to 33% graduating between 2009 and 2013. Institutions should actively seek to increase the diversity of PhD students in Australia, and promote genuine equity of access and opportunity in all positions within astronomy. Australian astronomy must specifically address the low level of female participation among Australia's professional astronomy workforce, which has remained at 20% over the past decade, and should aim for at least 33% participation by women across all

"**ENGAGEMENT OF ASTRONOMERS IN TEACHER-TRAINING PROGRAMS AND CURRICULUM DEVELOPMENT AT THE PRIMARY AND SECONDARY LEVELS IS RECOMMENDED AS THE HIGHEST PRIORITY**"

Teachers participating in the 2013 Astronomy from the Ground Up Galileo Teacher Training Program workshop in front of the CSIRO Parkes radio telescope. CREDIT R. HOLLOW

levels of employment by 2025 in alignment with the current PhD student cohort. The Pleiades Awards, which recognise organisations in Australian astronomy that take active steps to advance the careers of women, provide an excellent example. Astronomy organisations in Australia should adopt principles that aim for at least 33% participation in Australian astronomy by women in 2025. Longer-term (five-year) postdoctoral positions with part-time options and support to return to astronomy research after career breaks are recommended. In addition, increasing the fraction of continuing positions relative to fixed-term contracts is also of importance to ensure a viable and stable career path for young researchers.

With the large rise in the number of PhD students in astronomy, training PhD students for careers both within and outside astronomy is essential. Astrophysics PhD students typically finish their studies having gained substantial problem-solving and statistical skills. A set of transferrable skills should also be developed as part of the astronomy PhD program, to provide highly skilled graduates for roles in the wider community. Universities should offer postgraduate and early-career courses that teach lateral skills, including expertise in managing large data sets, programming in languages in demand by industry, training in industry practices, professional project and management skills. Retraining workshops such as the 'Science to Data Science (S2DS)' workshops are recommended to ensure that students are prepared for potential future careers outside astronomy, or the new key roles for HPC-trained personnel within astronomy research programs.

It is critical for universities to foster an environment where a wide range of career choices and opportunities are available to postgraduate students through supervisor training, mentoring, and by providing contacts with former graduates who entered non-astronomy careers. Universities should also provide formal recognition and support of scientists for developing, maintaining, and teaching transferrable skills, such as software development and data science. These scientists will provide key role models to the rising pool of highly skilled astronomy graduates that will transition to careers in areas including, but not limited to, industry, computer science, and big data.

Capturing and keeping the interest of the next generation

Novel education programs bring astronomy up-close and personal to today's students—who are also tomorrow's astronomers! Here are three examples:

TELESCOPES IN SCHOOLS (TIS) places research-grade telescopes into secondary schools in metropolitan Melbourne and regional Victoria and delivers training programs for using them. Started in 2012 by The University of Melbourne's Astrophysics Group, it has many education and industry collaborators including Museum Victoria, Quantum Victoria, and CSIRO. TiS has set up telescopes in 11 schools, reached over 3,100 students, held almost 200 astronomy sessions and hosted its first Astrophotography Competition. The project's website hosts photos and blogs posted by students, teachers and outreach participants showing what individual schools are doing. In 2013, the number of Pascoe Vale Girls College students studying physics doubled (with TiS cited as the main contributing factor) and year 12 graduates who had taken part in TiS all took up a STEM-related degree.

Students from Pascoe Vale Girls College undertaking Solar observations as part of the Telescopes in Schools program. CREDIT: L. ANKERS

CAASTRO IN THE CLASSROOM (CITC) engages Australian school students with research scientists and PhD students in a virtual meeting room, taking advantage of the infrastructure provided within the Connected Classroom initiative of the New South Wales Government. Locally coordinated at The University of Sydney, sessions may include short research presentations, discussions of a particular aspect of

5 EDUCATION: THE FOUNDATION OF ASTRONOMY

astronomy or physics, or a forum on life as a scientist. In the 2013 school year, CitC offered over 20 sessions to over 400 students from about 30 schools. Also in 2013, CitC went to China where students from three schools learned about 'Cosmic Engines in the Early Universe' and contributed to an excellent interactive question-and-answer session. 2014 saw the trialling of curriculum-focused lectures developed in close collaboration with the New South Wales Department of Education. The lectures are most popular with remote and rural New South Wales schools and future plans are to broadcast to Queensland schools.

PULSE@PARKES, CSIRO's PULsar Student Exploration online at Parkes, gives high school students the opportunity to control the 64-metre Parkes telescope remotely over the internet in real time. Guided by professional astronomers, students observe pulsars and use the data to determine the distance to the pulsar. The student's data feeds into a growing database used by professional researchers. About 1,200 students from around 100 schools have taken part and sessions have been held across Australia, in the UK, the Netherlands, Japan and the USA. PULSE@Parkes engages students in science through a stimulating experience of doing real science using a major national facility.

PULSE@Parkes astronomer Dr Matthew Kerr with students from Brigidine College St Ives in an observing session at the ATNF Science Operations Centre. CREDIT: R. HOLLOW

Where do the astronomy PhDs go?

A PhD in astronomy both prepares students for work in academia and provides the general skills to excel in wider society. To illustrate, we summarise the post-PhD career paths of former students during the five-year period from 2010–2014. Approximately 50% currently have jobs in astronomy, 30% have jobs in other fields, with the current positions of 20% being unknown. For those known to be working outside astronomy, about 30% have jobs in other research or scientific disciplines, 50% work in information technology or analytics, and the remaining 20% work in a range of sectors including teaching, technology development, finance, and administration. Three examples below illustrate this diversity.

DR ALICIA OSCLACK, HEAD OF BIOINFORMATICS, MURDOCH CHILDRENS RESEARCH INSTITUTE Dr Alicia Oshlack completed her PhD at The University of Melbourne on the topic of the central structure of radio quasars in 2003. Alicia continued in astrophysics for a further year before moving from using mathematics to look at the heavens to using mathematics to look at genetics. She made this transition at the Walter and Eliza Hall Institute where she worked in the Bioinformatics Division. In 2011 Alicia moved to the Murdoch Childrens Research Institute in Melbourne where she is the head of the bioinformatics research group. Alicia was honoured with the 2011 Ruth Stephens Gani Medal from the Australian Academy of Science for her work in human genetics and evolution.

DR WILFRED WALSH, COMPANY FOUNDER OF BIOSPHERE CAPITAL Dr Wilfred Walsh, whose early research focused on studies of galaxies to investigate star formation, dark matter and dark energy, completed his PhD in astrophysics from The University of New South Wales in 1993. He has worked on astrophysics technology research at CSIRO in Australia, Max-Planck Gesellschaft, Germany, and Harvard University, USA, specialising in radio detectors and installations in Antarctica, where he spent the 2002 winter stationed at Amundsen Scott South Pole Station. Since 2006, he has worked in the renewable energy sector as a business owner, as well as a researcher and a university educator. He currently leads a Solar Potential and Energy Meteorology group at the National University of Singapore, and he is the Managing Director for Biosphere Capital Pty Ltd, that he founded in 2007 to provide technical and financial consultancy services to the renewable energy industry.

DR ILANA FEAIN, CO-FOUNDER AND CEO OF NANO-X Dr Ilana Feain leads the development of a novel and cost-effective radiotherapy machine designed to level the playing field in global accessibility to equitable cancer treatment. Ilana obtained her PhD in astrophysics from The University of Sydney in 2006, and became a research astronomer and project scientist on the Australian Square Kilometre Array Pathfinder (ASKAP) at CSIRO Astronomy and Space Science. This led to Ilana

developing a cross-disciplinary research program to enable ASKAP's novel receiver technology to be used beyond astronomy, including in health and defence. Ilana then made a major career change in 2014, when she moved into medical physics, working in the Radiation Physics Laboratory at the School of Medicine of The University of Sydney. In her current role with Nano-X, Ilana is motivated to improve accessibility of radiotherapy treatment for cancer. Radiotherapy is the most cost-effective way to treat patients both curatively and palliatively, but the current generation of radiotherapy machines cost $5–6M. Ilana's team invented and patented Nano-X to deliver best-practice treatment at about 10% of the cost of current machines.

Dr Ilana Feain working with a dosimetry phantom in the Nano-X radiation shielded bunker at Nelune Comprehensive Cancer Centre. CREDIT: P. LAZARAKIS

6 Research: Questions for a new decade

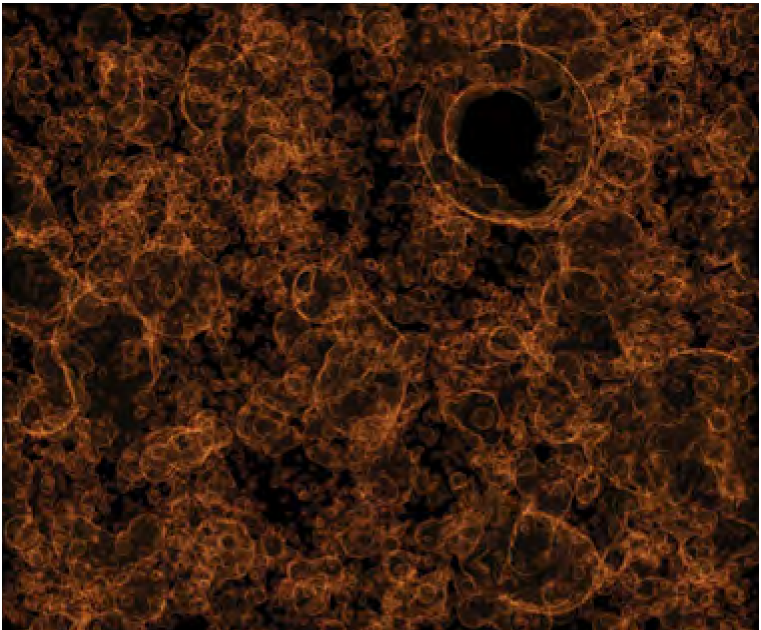
"AUSTRALIAN ASTRONOMERS ARE ADDRESSING FUNDAMENTAL QUESTIONS ABOUT OUR UNIVERSE"

Astronomy is entering a new era of exploration. Extremely large optical/IR telescopes will allow studies of stars and galaxies at the dawn of the Universe, and the study of planets similar to the Earth around other stars. Giant radio telescopes will reveal how early galaxies transformed the infant Universe. The expected and long-awaited detection of gravitational waves will open a window to the most extreme environments in the Universe. This far-reaching new knowledge will confront theoretical models and supercomputer simulations to achieve an unprecedented understanding of the Universe, as well as test the laws of fundamental physics that have underpinned technological society for hundreds of years.

This Decadal Plan identifies the following fundamental science questions in which Australia is poised to make world-leading contributions:

1. How did the first stars and galaxies transform the Universe?

During the first few hundred million years after the Big Bang, the cosmos changed from a cold and dark Universe to a hot and luminous birthplace for stars and galaxies. During the past decade, astronomers have glimpsed this era by discovering galaxies in the distant Universe and by finding stellar relics that formed during the first few hundred million years after the Big Bang. The next decade will unveil the early Universe for the first time. The MWA and SKA low-frequency telescopes will be used to trace the dramatic transformation of the young Universe that followed the formation of first generation of galaxies, while 8-metre class optical/IR telescopes and ELTs will allow study of these first



Simulation of the reionization of the Universe by the first galaxies showing the structure ionized gas around the first galaxies. The simulated region of the Universe measures several hundred thousand light-years on a side. CREDIT: S. MUTCH

"THEORETICAL AND COMPUTATIONAL ASTROPHYSICS HAS GROWN TO BECOME A FOCUS ACROSS ALL AREAS OF STRENGTH IN AUSTRALIAN ASTRONOMY RESEARCH"

stars and galaxies in unprecedented detail. Through large-scale discovery and exploration with the next-generation of telescopes, combined with state-of-the-art numerical simulation, Australian astronomers will reveal the earliest stars and galaxies, and track the dramatic changes that occurred in the infant Universe.

2. What is the nature of dark matter and dark energy?

Dark matter and dark energy comprise more than 95% of the Universe, and yet their nature remains unknown. The properties of dark matter and dark energy govern the formation and evolution of galaxies, their internal structure, and how galaxies are distributed across the Universe. In the past decade,

“THE PAST DECADE HAS SEEN A LARGE RISE IN AUSTRALIAN SCIENTIFIC IMPACT FROM INTERNATIONAL FACILITIES”

astronomers have measured the amount of dark matter and dark energy in the Universe. In the coming decade, Australian astronomers will use surveys with next-generation 8-metre class optical/IR telescopes and ASKAP to measure the expansion rate and growth of structure of the Universe. Massive computer simulations of this growth, along with data from next-generation gamma-ray, neutrino, radio and optical/IR telescopes will probe the nature of dark matter and dark energy.

The luminous IR galaxy ESO 440-IG058 imaged with the ANU-built Gemini South Adaptive Optics Imager. The image shows two interacting galaxies driving star formation activity, plus a previously unseen edge-on disk galaxy.
CREDIT: S. RYDER

3. How do galaxies form and evolve across cosmic time?

In the early Universe, gas clouds clumped together to form the first galaxies. Over the next 13.5 billion years, these galaxies collided and accreted gas, growing into the massive galaxies that surround us today. Observations of the distant Universe have shown that galaxies evolved from being clumpy and disordered into smooth spirals and ellipticals. In the coming decade, ELTs will facilitate detailed observations of galaxy structure at unprecedented distances. New coordinated Australian-led multi-wavelength surveys of gas and stars with ASKAP and the AAT will reveal the birth and life of galaxies, including our Milky Way. Next-generation surveys using the SKA, 8-metre class optical/IR telescopes, and world-leading Australian instrumentation to facilitate massively multiplexed spectroscopic surveys combined with theoretical simulations will be instrumental for understanding how galaxies work throughout cosmic time. Through this coordinated approach, and new technologies allowing spectra to be measured for thousands of galaxies in both spatial dimensions, Australian

astronomers will determine how angular momentum and mass build up in galaxies, why stars stop forming, how supermassive black holes form and regulate galaxy growth, and unravel the history of the Milky Way.

4. How do stars and planets form?

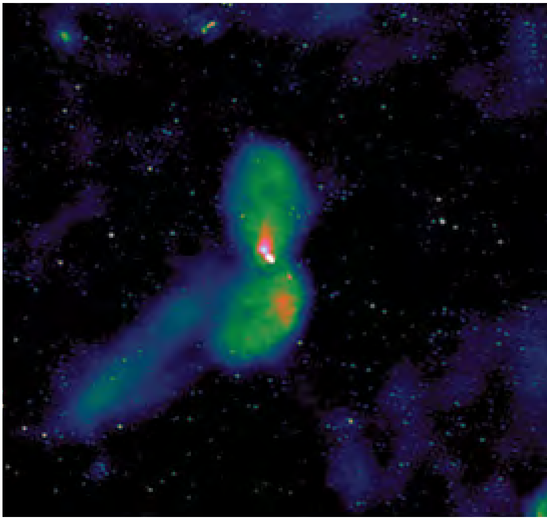
How the turbulent, magnetic interstellar gas is turned into stars and solar systems is core to understanding the very existence of humankind. Primary challenges include what determines the distribution of stellar masses, discovering Earth-like planets around solar-like stars, and searching for signatures of life. In the coming decade, Australian astronomers will combine theoretical simulations with observations from the ATCA and new facilities including the Atacama Large Millimeter/submillimeter Array (ALMA) and the James Webb Space Telescope (JWST), to address key fundamental questions in planet formation and evolution, including how stellar and planetary systems form and what are their birth characteristics. Revolutionary improvements in spatial and spectral resolution afforded by 30-metre class telescopes like the GMT will facilitate measurement of the structure and composition of extra-solar planets and their atmospheres, while programs using 8-metre class optical/IR telescopes will address whether habitable planets are common.

5. How are elements produced by stars and recycled through galaxies?

The Big Bang produced all of the hydrogen in the Universe and most of the helium, together with traces of lithium. All other elements have been forged deep in the interiors of stars. Sophisticated supercomputer simulations allow the chemical compositions of stars, including the Sun, to be measured. We now know that the elements transform the way new stars are born, the way planets are formed around young stars, the way stars live and die, and the way stars assemble into new galaxies. Australian astronomers pioneered the technique of galactic archaeology, and in the coming decade will use large-scale surveys of stars and galaxies using massively multiplexed spectroscopy and 8-metre class optical/IR telescopes to address how the first and subsequent generations of stars produced the chemical elements that enrich the Universe, and how these elements were assembled into galaxies including our Milky Way. The revolutionary sensitivity of ELTs will be used to

"WORLD-LEADING ASTRONOMY RESEARCH REQUIRES RADIO AND OPTICAL TELESCOPES WITH A RANGE OF CAPABILITIES, AS WELL AS SUPERCOMPUTING FACILITIES FOR THEORETICAL AND COMPUTATIONAL RESEARCH"

understand the properties of ancient stars born at the dawn of the Universe and discovered in Australian-led surveys, improving our understanding of the first generation of galaxies and their role in the early history of the Universe.



An MWA image of the famous nearby radio galaxy Centaurus A. Centaurus A is approximately 10 degrees in angular extent, showing the superb widefield capabilities of the MWA. CREDIT: R. WAYTH

6. What is the nature of matter and gravity at extreme densities?

The most extreme environments in our Universe can be probed through bursts of electromagnetic radiation, particles and gravitational waves. Over the next decade, the expected detection of gravitational waves from colliding black holes and collapsing stars, using precision pulsar timing with the Parkes telescope and the SKA mid-frequency instrument and ground-based gravitational wave detectors, will open a new window for astrophysics. Australian astronomers will develop multi-messenger astronomy, by combining electromagnetic radiation from radio to X-ray energies, gravitational waves, cosmic rays and neutrinos. These methods will test Einstein's theory of relativity during black hole mergers, probe the interiors of pulsars and the origin of fast radio bursts, and reveal how cosmic rays are accelerated to the highest energies.

Three of the four 8.2-metre optical/IR Very Large Telescopes on Cerro Paranal in northern Chile.
CREDIT: ESO

7 Strategic plan: Roadmap for the next decade

"ASTRONOMY IS BECOMING INCREASINGLY GLOBAL"

Conducting world-leading astronomy research requires an infrastructure portfolio that includes radio and optical/IR telescopes with a range of capabilities, as well as powerful supercomputing facilities for theoretical and computational research. Increasingly, forefront research will require the inclusion of higher energy observations to enable the study of astrophysics across the entire electromagnetic spectrum.

7.1 An evolving portfolio of astronomy capability

Current domestic radio telescopes include the Parkes telescope, the Australia Telescope Compact Array (ATCA) and the Australian SKA Pathfinder (ASKAP) operated by CSIRO, and the Murchison Widefield Array (MWA) operated by Curtin University. Optical/IR facilities include the Anglo-Australian Telescope and the UK Schmidt Telescope operated by the Australian Astronomical Observatory and the 2.3 metre and SkyMapper telescopes operated by the ANU. Several Australian universities operate research telescopes that play valuable roles in training, research and innovation. The importance of these facilities reaches beyond their scientific output to training of astronomers who will play a leading role in the scientific utilisation of the global astronomy facilities. The national infrastructure for astrophysical theory encompasses high performance computing (HPC) facilities at the National Computational Infrastructure (NCI; ACT), Swinburne University of Technology (Victoria), Monash University (Victoria), and the Pawsey Centre (Western Australia).

To maintain international competitiveness in astronomical research, Australia's observational portfolio will evolve towards large-scale international facilities over the coming decade. Table 7.1 illustrates how a broad suite of major

national and international facilities, providing a combination of radio and optical/IR telescopes alongside computational capability, will enable Australian astronomers to answer the fundamental astronomical questions posed in this Decadal Plan. None of these six big questions can be answered with a single capability, or studied at a single wavelength; each requires coordinated efforts across the full multi-wavelength range of facilities, with analysis and interpretation underpinned by computational infrastructure.

During the first half of the coming decade, the UK Schmidt optical telescope and the Parkes telescope will help us measure the components of the cosmic web and understand matter and gravity at extreme densities. The AAT and 8-metre class telescopes will unravel the history of the Milky Way, and discover and characterise planets around other stars in conjunction with space-based telescopes. During the middle of the decade, coordinated efforts on ASKAP, an upgraded MWA, ATCA, AAT, and 8-metre class telescopes will be used to understand the evolution of galaxies, the influence of dark matter, and the nature of the earliest galaxies. Universities, often in partnership with the national observatories, will have a key role in the provision of world-class capabilities that complement nationally supported infrastructure in specialised areas such as very long baseline interferometry and time-domain astronomy, or instruments dedicated to specific research projects.

By the end of this Decadal Plan period, the international Giant Magellan Telescope (GMT), and the first phase of the Square Kilometre Array (SKA) facilities including the mid-frequency and low-frequency components are due to be completed, reducing the requirement for smaller-scale domestic facilities. Australia should continue to pursue membership of the SKA, building on successes of the past decade, and the advantages provided by its status as a host nation. ASKAP will continue to underpin the SKA mid-frequency program as the core survey instrument. Australian membership of the SKA and the GMT will provide an unprecedented new view of the distant Universe, tracking the evolution of galaxies over most of the observable age of the Universe, probing the environments of the first stars and galaxies, and testing our understanding of gravity. The spectacular sensitivity and resolution of the GMT will transform our understanding of the formation of stars and planets and discover and study Earth-like planets and their atmospheres. By then, 8-metre class optical/IR telescopes will provide 'workhorse' observational facilities for Australian astronomers, with important roles including selecting targets for the GMT.

Table 7.1: Major national and international facilities required to answer the fundamental questions outlined in this Decadal Plan. Dark and light shading represent critical and supporting capabilities within the Australian astronomical context.

	MWA -> SKA low-frequency	ATCA, Parkes -> SKA mid-frequency	ASKAP	30-metre class optical/IR facilities (ELTs)	8-metre class optical/IR facilities	High performance computing	AAT and 8-metre class wide-field multi-object spectroscopy	High energy facilities	Ground-based gravitational wave detectors	ALMA
1) How did the first stars and galaxies transform the Universe?										
2) What is the nature of dark matter and dark energy?										
3) How do galaxies form and evolve across cosmic time?										
4) How do stars and planets form?										
5) How are elements produced by stars and recycled through galaxies?										
6) What is the nature of matter and gravity at extreme densities?										

"LONG-TERM PARTNERSHIP OF AN 8-METRE CLASS TELESCOPE IS THE MOST PRESSING UNRESOLVED ISSUE FOR THE AUSTRALIAN ASTRONOMICAL COMMUNITY"

In this context, the lack of secure long-term partnership of an 8-metre class optical/IR telescope at the beginning of the 2016–2025 period has placed Australian astronomy in a critical situation. To maintain Australian leadership in optical/IR astronomy, and achieve ground-breaking discoveries over the coming decade in all areas, from planets, stars and galaxies, through to the nature of dark matter and dark energy, Australian astronomers require a 30% share of an 8-metre class telescope, or equivalent, which is typical of other OECD countries of similar size. This represents an increase relative to the recommendation of a 20% share from the last Decadal Plan, reflecting both the growth in the Australian astronomy community over the past decade, and the continued transition of workhorse astronomical instruments from 4-metre telescopes to international 8-metre class optical/IR telescopes. A 30% share corresponds to two observing nights every three years[1] per professional optical/IR astronomer in Australia, which is a modest requirement by international standards. This Decadal Plan stresses the importance of partnership in an optical/IR 8-metre class facility (as opposed to short-term cost-per-night access) in order to facilitate opportunities for innovation in areas of demonstrated Australian strength including astrophotonics, astrorobotics and all-sky surveys. Long-term partnership is essential both to maintain scientific leadership within 8-metre class telescopes, and also for continued development of Australian astronomy in the ELT era. Partnership in a leading international observatory is the highest priority for optical/IR 8-metre telescope access.

An excellent option for satisfying Australia's optical/IR capability would be provided by membership of the European Southern Observatory (ESO), as identified in the mid-term review of the 2006–2015 Decadal Plan. Australian membership of ESO would meet the proposed goal of access to 30% of an optical/IR 8-metre class optical/IR telescope. ESO provides 8-metre class optical/IR telescopes with the broadest available world-class instrument suite that would best meet Australian scientific goals. Membership of ESO would also allow Australian instrument builders to maintain their world-leading

1 Data acquired from two nights represents the benchmark for a data set leading to publication on leading 8-metre class optical/IR telescopes.


The 4-metre AAT mirror after its aluminising in 2014. CREDIT: A. GREEN

capabilities in instrumentation development and provide opportunities for industry engagement in large construction projects. ESO additionally provides a broad suite of additional capability supporting astronomical science including the 39-metre European ELT (E-ELT) and Atacama Large Millimeter/submillimeter Array (ALMA) telescopes. ALMA will deliver new capabilities in both angular resolution and wavelength parameter space, and is essential for the studies of star and planet formation, and of the gas that fuels star formation in distant galaxies.

"BY 2020, STRATEGIES MUST BE IN PLACE TO TRANSITION FACILITIES SUCH AS THE PARKES TELESCOPE, ATCA, AND THE AAT TO NEW ROLES WITHIN THE ELT AND SKA ERA"

To develop research capacity for next-generation telescopes, Australian astronomers must lead and engage in major research and instrumentation programs on intermediate-scale facilities. Partnership in an 8-metre class optical/IR telescope before and during the GMT era is crucial to allow Australian instrument builders to continue their demonstrated innovation and excellence, and to drive the scientific direction of telescopes. Australian astronomers are now beginning large survey programs with ASKAP and the MWA. These surveys will play critical roles in providing legacy data for SKA science, and will allow Australian astronomers to develop the radio expertise and technical capacity required to build, operate and scientifically exploit the SKA. Continued development of low-frequency radio astronomy during the coming decade is an important goal which will enable studies of the first galaxies, and leverage the key advantages of, and investment in, the Murchison

SKA—Science plus

In pursuing answers to some of science's biggest questions, Australia's involvement with the Square Kilometre Array (SKA) will also bring net gains to Australia in other ways. A strategic workshop of the European Cooperation in Science and Technology framework found that for the SKA, 'the benefits in terms of innovation, capacity and capability enhancement, and indirect societal impacts are expected to be significant and important'.

The benefits to Australia from the SKA have already been considerable in terms of establishing significant infrastructure, installing fibre-optic broadband to regional and remote areas of Western Australia, attracting high-calibre scientific and engineering expertise and international collaborations, and providing employment and services such as science education.

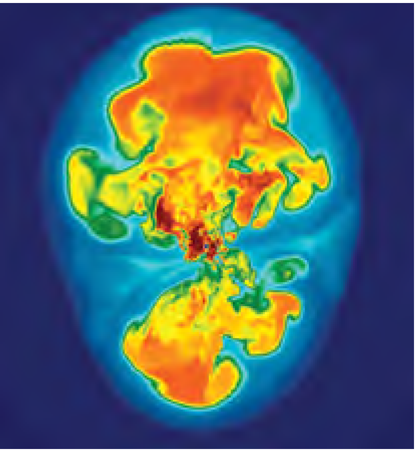
The ground-breaking nature and substantial scale of Australia's participation in the SKA will inevitably lead to novel and/or improved technologies for constructing and supporting its multiple radio antennas. Technologies developed by the SKA to meet scientific and practical needs for electricity generation and improved communications, can be applied in other settings. New knowledge can lead to unexpected shifts in our understanding of areas such as complex system integration, electronics, digital receivers, renewable energy and information and communications technology. Australia's investment in the SKA will deliver a net positive tangible economic outcome over the anticipated lifetime of the SKA. Additional intangible benefits including for industry, and flow-on revenue are also expected.

Developed for the Australian SKA Pathfinder telescope, phased array feeds are cutting-edge 'radio cameras' that enable wide-angle surveys of the sky; they are also showing promise for use in medical imaging. Analysing the huge amount of data generated by the multiple antennas will overwhelm the fastest supercomputers available in 2015; SKA research will lead the way in developing a new kind of high-speed network. Being situated in a remote area, SKA energy requirements will speed up technology development for renewable energy generation and distribution.

Significant electronics packages for the Murchison Widefield Array, a low-frequency SKA precursor, were developed by a small-to-medium enterprise in Western Australia, allowing the company to upskill its workers on a challenging project.

It is impossible to predict which, when and how technical innovations devised by the SKA's astronomy-industry-technology partnership will leap into other markets; but leap they will, and the return on investment can be impressive—just look at the discovery of wi-fi technology, based on astronomy techniques and developed at CSIRO.

Artists impression of the SKA low frequency dipole antennas deployed at the MRO. CREDIT SKA ORGANISATION



3D simulation of a supernova explosion simulated using HPC facilities at NCI and Swinburne. CREDIT: B. MUELLER

"THIS DECADAL PLAN IDENTIFIES FUNDAMENTAL SCIENCE QUESTIONS IN WHICH AUSTRALIA IS POISED TO MAKE WORLD-LEADING CONTRIBUTIONS"

Radio-astronomy Observatory (MRO) during the pre-SKA period. An expanded MWA should be operated until at least the middle of the decade with early science from the SKA low-frequency telescope expected to start in the later part of the decade. The ASKAP telescope must be available to conclude science survey projects, with upgrades and incorporation a later possibility as part of Australia's partnership in the SKA. Early SKA1 mid-frequency science is expected to commence towards the end of the decade.

Investment in the international facilities of the GMT and SKA era must be accompanied by commensurate development of optical/IR and radio research capacity and training. There is an extremely important role for facilities including 8-metre class optical/IR telescopes and the SKA precursor telescopes as training grounds to prepare Australian PhD students and postdoctoral researchers for the new global facilities. This investment is necessary to capitalise on the scientific opportunities, and maximise scientific and economic returns. Australian universities have a critical role in providing this training in collaboration with the national observatories.

Theoretical astrophysics has a strong tradition within Australia and has undergone significant growth over the past decade. Australian theorists work in all areas of astronomy, including modelling of observational results from Australian facilities and state-of-the-art simulations of stars and galaxies. This combined effort currently represents more than one-third of the scientific activity and impact in Australian astronomy. Theoretical and computational research in Australia will remain strong over the coming decade with the need for predictions and theoretical interpretation of large observational surveys and is therefore of key importance for achieving the primary scientific goals outlined in the Decadal Plan. To achieve these scientific goals, the astronomical community should work to increase linkages between the theoretical and

observational communities on projects of common interest, and also develop strategies to support career paths for theoretical astronomers whose research programs are not tied to specific observational infrastructure or programs.

National investment in hardware, software systems and high performance computing facilities is essential to support theory, data-intensive analysis, and archiving. The continued evolution towards large-scale data-rich facilities heightens this need, making such capabilities an integral part of any new telescope. Over the next decade, the increasingly panchromatic requirements of astronomy will bring together data of different types and wavelengths by connecting independent data hubs. Continued planning for such a federation of data sets will allow the Australian community to maximise the scientific exploitation of existing and anticipated major astrophysical data sets. The cost of such data federation, including the HPC professionals to develop and maintain them, must be budgeted for when projects are being planned.

To maximise the scientific exploitation of existing and anticipated major astrophysical data sets nationwide, funding for data-intensive analysis and high performance computing is therefore a high priority. Based on the growth of the Australian theoretical astrophysics community, the importance placed on simulation in answering Australian astronomy's science questions, and the growing need for processing of large data products from telescopes including ASKAP and the MWA, the estimated HPC resource needed for Australian astronomy to achieve its goals corresponds to approximately the equivalent of 30% of a top-100 supercomputer[2].

7.2 Mid-scale priorities

This Decadal Plan outlines a vision of Australian astronomy engaged in partnerships to operate the next generation of global facilities including the SKA and the GMT, supported by access to mid-scale international facilities including MWA, ASKAP and 8-metre class optical/IR telescopes, as well as HPC capability and expertise. These facilities will form the core of Australia's observational capability, but success against the Decadal Plan goals will require complementary investments at a smaller level. Priority among additional

2 We note that this requirement is in addition to the real-time HPC resources required to produce the initial archived data products from data-intensive telescopes such as ASKAP and the MWA.

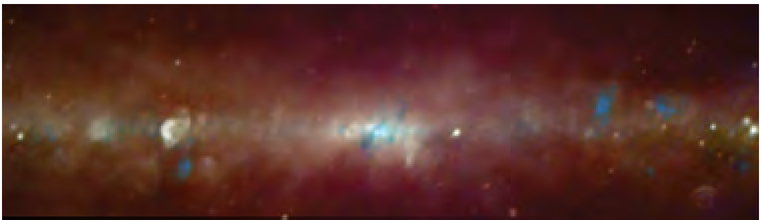
Assembly of the suspension system for the transmission monitor telescope at the LIGO Hanford Observatory (USA). CREDIT: LIGO COLLABORATION

investments should maximise Australia's capacity to deliver against the capability needed to address the key science questions (e.g. as illustrated in Table 7.1).

Building on Australia's world-leading expertise in optical multi-object spectroscopy, development of an 8-metre class optical/IR wide-field spectroscopic survey telescope towards the end of the decade would complement Australian optical/IR astronomers' leading priority of access to a multi-purpose 8-metre class optical/IR observatory. Such a facility, most likely constructed by an international partnership, would address several of the fundamental astronomical questions of the coming decade, including the nature of dark matter and dark energy, the formation and evolution of the Milky Way and how stars and galaxies process chemical elements. It would also provide follow-up spectra of objects identified by the SKA and imaging telescopes like the US-led Large Synoptic Survey Telescope (LSST). Involvement in the LSST, especially in combination with a large, wide-field optical/infrared spectroscopic survey facility, would provide excellent synergies with the next generation of radio facilities (ASKAP, MWA, SKA), and build on Australia's leadership in all-sky surveys.

Substantial opportunities exist, at relatively modest investment levels, for participation in cutting-edge international high-energy telescopes such as the Cherenkov Telescope Array for studies of gamma-rays, upgrades to cosmic ray and neutrino telescopes, and Antarctic facilities for infrared and terahertz observations of distant star-forming galaxies. Australia is a partner in the High Elevation Antarctic Terahertz (HEAT) telescope at Ridge A—the world's pre-eminent THz site, which provides THz data to the Australian community. Additionally, continued Australian involvement in Antarctic astronomy with a focus on current and planned infrared observatories such as AST3 offers strategic links with China.

International gravitational wave experiments and observatories are on the cusp of detecting emission from the coalescence of neutron stars and black holes, thus testing the predictions of general relativity and transforming our understanding of the Universe. Australian researchers are at the forefront of this effort through membership of the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) gravitational wave experiment and the International Pulsar Timing Array. Following the initial detection of such events, Australia should continue its leadership role in pulsar timing array projects and consider expanded participation in future upgraded or new international ground-based gravitational wave facilities.



MWA image of the centre of the Milky Way. CREDIT: N. HURLEY-WALKER

7.3 Transition of astronomy to a global science

Over the coming decade, the national observatories will transition from their present role of operating Australia's domestic telescopes to a role dominated by managing access to international-scale facilities. As part of this role, the national observatories will conduct and oversee the development of new instrumentation and provide training for users of these facilities. New

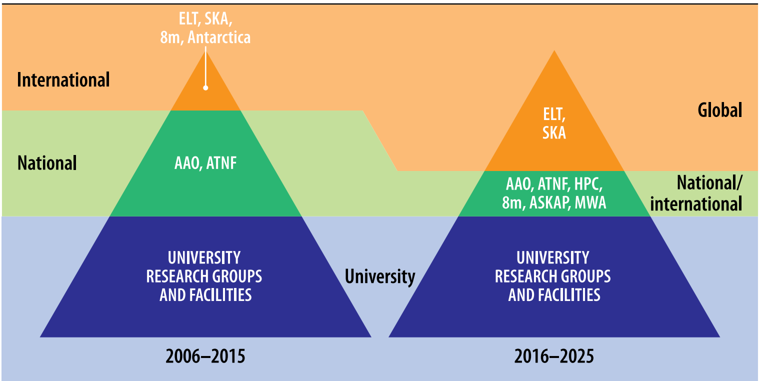
instruments currently due for deployment on domestic national facilities and overseas telescopes will ensure that Australia remains at the forefront of world research during at least the first half of the coming decade. By 2020, strategies must be in place to transition current domestic facilities such as the Parkes telescope, ATCA, and the AAT to new roles within the ELT and SKA era, or to prepare for closure. The Mopra telescope is currently undergoing this transition. A mid-decade review of these facilities should consider their role, impact and funding model for the latter half of the decade. Timescales for the next generation of instruments must be considered to ensure that existing telescopes are not defunded prematurely, causing a capability gap. This is particularly important with respect to key science programs for the SKA including pulsar timing that require continuous coverage in time. International partnerships or university contributions could be sought to allow national funding to be redirected to the next generation of key astronomical facilities.

Over the past decade, approximately 25% of Australia's impact-weighted activity was conducted using facilities in which Australia was not a partner. Australian astronomers compete for this time within the international research community, and are well placed to take advantage of the increasingly international research environment. Australia will continue to benefit from access to these international space-based as well as ground-based optical/IR and radio telescopes which are provided through a range of mechanisms that encourage scientific exchange and the best scientific utilisation of infrastructure. Continuing to provide overseas astronomers with access to world-class Australian facilities is an important component in retaining access for Australian astronomers to the widest possible range of international capabilities.

> **"AUSTRALIA'S ASTRONOMICAL RESEARCH EXCELLENCE RESTS ON CONTINUED PARTNERSHIP BETWEEN ASTRONOMICAL OBSERVATORIES AND THE UNIVERSITIES"**

Australian astronomers have benefitted enormously from international space facilities such as the Hubble Space Telescope (HST) and the Kepler satellite. Indeed, space-based observations formed 30% of Australia's scientific impact in optical/IR astronomy during the past decade. Upcoming space telescopes such as the National Aeronautics and Space Administration's (NASA's) James Webb Space Telescope (JWST) will be incredibly influential in the future as they

Figure 7.1: Evolution of the Australian Astronomical Pyramid. The proposed split in 2005 between funding at the International:National:University levels was 1:6:12. At the end of the period 2016–2025, we project that these ratios will be approximately 4:3:12, reflecting the increasingly global focus of Australian astronomy.



shed light on the most distant galaxies and reveal the conditions on planets around other stars. Australian astronomers should consider formation of a national body that supports co-ordination of engagement with space-based telescopes.

Realisation of Australian astronomers' ambitions will require an integrated cooperative effort between universities, the AAO and ATNF who run the national facilities, and the international SKA, GMT and ESO organisations. Figure 7.1 symbolises these linkages via an astronomical pyramid, and shows how this pyramid will evolve from the one described in the past Decadal Plan. Universities play the key role in conducting research and in training the astronomical and wider STEM workforce. University-operated research telescopes play valuable roles in training astronomers who will play a leading role in the scientific utilisation of the global astronomy facilities. To perform these tasks, universities must work closely with the national organisations that provide the primary technical expertise to manage scientific facilities and drive innovation, and with the appropriate organisations to help deal with the massive data flows from future telescope projects. The role of the national observatories will necessarily evolve to provide the local training support required for users of the large international facilities. Thus, the mid level of the pyramid has evolved from the national facilities in 2005 to include the national

observatories and access to international workhorse instruments. The levels of the pyramid are tied together by a complex network of inter-linkages between the members of the Australian astronomical community. Research collaborations span all levels of the pyramid.

The missing layer in the era of data intensive research

As telescopes become larger and more complex over the next decade, they will generate orders of magnitude more data than telescopes of the past. The raw data rates produced by the emerging generation of astronomy facilities are pushing technology and techniques as hard or harder than any other application. Industry sees this as an opportunity, driving the development of products that can be applied in a wide variety of markets. Astronomers recognise that data-intensive research will be an important theme in the next decade and beyond. This Decadal Plan reflects this recognition through community support for initiatives such as the All-Sky Virtual Observatory (ASVO).

The development and effective utilisation of the ASVO and other data-related initiatives will require the astronomy community to foster a new type of scientist, dedicated to data-intensive activities—managing, curating, manipulating, processing vast volumes of data, extracting information from it and making data and information available and accessible to other scientists. Currently these scientists are largely missing from the astronomy community and a challenge for the next decade will be to train such scientists and create career paths for them. These data experts will be critically important for the SKA and its precursor instruments in Australia.

Data-intensive scientists are likely to be multi-disciplinary and will likely have to move between academia and industry in order to bring solutions from outside astronomy. This need is an opportunity for astronomy to embrace industry–academic engagements, as industry has similar requirements across a range of different markets.

Embryonic work in this direction is already underway. An example of an initiative that may grow to meet astronomy and industry requirements is the Exascale Data Alliance (EDA). The EDA is industry-led (CISCO) and is bringing together academia, industry, and government agencies to explore the development of a centre motivated by the grand challenges of the SKA that will link academia with industry via physical co-location and shared challenges, encouraging mixing across the range of industry and academic experiences. A central theme of the EDA will be the training of undergraduate and graduate researchers, broadening their skills and encouraging careers that move back and forth between the academic and industry worlds. The benefit will be innovative and effective solutions to problems of importance to industry and the research community.

8 Innovation: Astronomy and industry

"THE ASTRONOMY COMMUNITY MUST WORK IN PARTNERSHIP WITH INDUSTRY TO REALISE ITS VISION"

The scale of future astronomical facilities demands skills, expertise and technologies beyond the current capabilities of Australia's academic community. Meaningful industry engagement is required to build partnerships that will design, develop and produce the next generation of astronomical instruments, and to harness the innovation flowing from fundamental research for commercial application. However, OECD data shows that Australian researchers are less engaged in collaboration with industry than their counterparts in other countries. Indeed, with only 3.3% of large Australian businesses collaborating with research organisations, Australia ranks 27th among the 34 countries in the OECD[1].

To fully prepare for active involvement in the 30-metre class ELTs and the SKA, a coordinated effort by the astronomy community and industry partners is required. A single central body should be established to promote and facilitate industry engagement. For industry, such an organisation would present a unified interface to astronomy projects and would provide detailed and background information on available projects, contracts, and opportunities for commercialisation of innovative technologies. For astronomers, such an organisation could assist with professional training, the development of appropriate contracting and procurement procedures, the development of best-practice models, and maintaining a contact list for industry expertise. Workshops and exchange programs could be facilitated by this organisation. Given the link with future facilities, a suitable host organisation could be

1 http://www.chiefscientist.gov.au/wp-content/uploads/STEM_AustraliasFuture_Sept2014_Web.pdf

Astronomy Australia Ltd (AAL), a national observatory organisation, or an industry-driven consortium such as the Australasian SKA Industry Consortium (ASKAIC).

Close links between astronomical research and industry naturally benefit both partners. The next generation of billion-dollar facilities like the SKA and ELTs provide significant opportunities for Australian industry to secure substantial contracts for the construction of the necessary infrastructure, instrumentation and technology. A large fraction of the Australian financial investment in current and future facilities is therefore expected to flow back to Australia and Australian companies. For example with membership of ESO, it is estimated that Australian industry would obtain contracts[2] worth approximately $13M p.a. Current industry engagement is focused around collaborative research and design contracts. Over the coming decade, there needs to be a transition to include collaborative research and design and industry-only design and supply.

In addition to ensuring that Australian industry benefits from the large construction and development opportunities being facilitated by the next generation of global facilities, it is of critical importance to maximise the flow of innovative technologies from fundamental research into commercial applications.

The majority of these opportunities will arise in the development of radio and optical/IR facilities. The major surveys of the coming decade will also provide opportunities in data-intensive research and high performance computing. To ensure that Australia maximises return from opportunities for partnerships of astronomy with industry, astronomers need to engage with industrial partners and potential partners to identify and overcome challenges. Challenges include understanding the differences between academic and industry approaches and practices, outlining the role of industry in instrumentation research and development, and analysing the risk and scalability associated with building cutting-edge astronomical instruments. Solutions include developing a commercial understanding within academia, fostering the exchange of personnel, and building long-term relationships between industry and academic partners.

2 Based on an average 70% of annual membership contributions being returned as contracts.

ASKAP industry engagement case study

The Australian SKA Pathfinder (ASKAP) is using cutting-edge Australian technologies to demonstrate the innovative capacity of Australian science and industry. A project on the scale of ASKAP relies on industry providing expertise in production, construction, installation and commissioning to demanding quantity and quality requirements, and introduces technical challenges that must be overcome in the design and construction of the telescope's components. As the Australia Telescope National Facility (ATNF) moves through the design, development, construction and operational phases of the ASKAP project, industry collaboration is playing a crucial role in research and development, and then prototyping and production of the antenna and receiver system components, processing electronics and support structures. Industry participation has created strong collaborations with a variety of organisations, among them research and development companies, and resulted in commercial contracts with high-volume manufacturers, technology systems vendors, site services and installations firms, and energy and data transmission specialists. Three examples illustrate these connections with both Australian and international partners:

- ATNF is working with *Innovation Composites* to develop and produce radio frequency interference (RFI) shielded, high-strength, weather-proof and insulated casings for ASKAP's innovative phased array feed (PAF) receivers that are lighter and more cost-effective than previous designs. The company works collaboratively with ATNF engineers to develop and manufacture a bespoke design that meets the special requirements demanded by the harsh working environment of ASKAP at the Murchison Radio-astronomy Observatory (MRO). Success was achieved through applying the specialist production knowledge of *Innovation Composites* to the problems of electromagnetic interference—a well-understood challenge for radio astronomy. The PAF casing design incorporates marine composites technology to manage structural loading, thermal insulation and environmental protection. The carbon fibre provides a level of RFI shielding, to prevent radio-frequency interference from the PAF's internal electronics impacting the radio-quiet atmosphere of the MRO.
- ATNF is working with *Puzzle Precision*, a high-quality electronic assembly service provider, to jointly develop and produce sophisticated electronic circuit boards and major components of the ASKAP digital systems. The high quality and accurate assembly equipment used by *Puzzle Precision* ensures large-scale delivery of the millions of intricate and complex components that make up these electronics boards for ASKAP.

Left: An assembly line of electronics boards for the ASKAP Mk II PAF at Puzzle Precision. Top: the specialised casing for the ASKAP Mk II PAF (inset), shown in context with an ASKAP antenna. Bottom right: An ASKAP Mk II PAF groundplane, assembled by Thermacore Europe. CREDIT CSIRO

- The second generation (Mk II) ASKAP receiver includes a requirement for a specially designed 'ground plane' to maintain a low and stable temperature crucial to system performance and reliability. *Thermacore Europe* is a world-leader in the field of passive thermal management systems, specialising in the custom design, development and manufacture of highly engineered components. Prototyping activities have led to a solution proven to meet the unique requirements of the ASKAP telescope, tested and validated against the complex ground plane specifications. The development of *Thermacore* ground planes for the Mk II ASKAP PAF has allowed minimised temperature gradients and a predictable temperature uniformity to be maintained across the highly sensitive electronics.

These are just some of the examples that led to ASKAP being recognised with the overall prize in the *Australian Innovation Challenge Awards*. The award cited the scientific, technical and logistical success of ASKAP, in taking expertise in the research and development of cutting-edge low-cost technologies, and working together with industry to put these technologies into production.

9 Governance: Managing Australian astronomy

“STRATEGIC MANAGEMENT ACROSS AUSTRALIAN ASTRONOMY WILL MAXIMISE OUR SCIENTIFIC INVESTMENTS”

Australia has a strong history of strategic planning of science priorities across all areas of astronomy through its decadal planning process. In response to the recommendations of the past Decadal Plan, Australian astronomers have developed a capacity for strategic management of investments across astronomy infrastructure through the formation of Astronomy Australia Ltd (AAL). AAL is a not-for-profit company limited by guarantee, whose members are all Australian universities and research organisations with a significant astronomical research capability[1]. AAL has worked with Australia's national observatories, astronomers at Australian universities, and the Australian Government to advance the goals in the previous Australian Astronomy Decadal Plan. The role of AAL has included management of National Collaborative Research Infrastructure Strategy (NCRIS) and Education Investment Fund (EIF) investments. AAL is a partner in the GMT, and represents Australia's interests in a range of international partnerships.

The AAO and ATNF continue to successfully facilitate access for Australian astronomers to world-class telescopes and manage Australia's national facilities on behalf of the astronomical community. Given the increasing alignment of scientific priorities and opportunities across optical/IR and radio astronomy, together with the transition to a more international focus for astronomy facilities over the next decade, the full portfolio of Australian astronomy

1 In 2015, AAL members included AAO, the Australian National University, CSIRO, Curtin University, Macquarie University, Monash University, Swinburne University of Technology, The University of Adelaide, The University of Melbourne, The University of New South Wales, The University of Queensland, The University of Sydney, The University of Tasmania, The University of Western Australia and The University of Western Sydney.

infrastructure may benefit from coordination of strategic oversight to maximise the effectiveness of investments in Australian astronomy. Australian astronomers should consider whether the national astronomy investment portfolio could be overseen by a central strategic body to provide an interface to government for provision of independent strategic advice regarding national and international-scale astronomy activities and operation of Australian-based facilities. If formed, such a body must be constituted with principles including that it maximise scientific returns for Australia, have the secure long-term funding required to effectively manage investments in astronomy research infrastructure, and be guided by and responsive to strategic priorities set by the astronomy community.

10 Resources: Realising the plan

"FUNDING A SKILLED WORKFORCE IS CRITICAL TO EXPLOIT THE NEXT GENERATION OF SCIENTIFIC INFRASTRUCTURE"

This Decadal Plan outlines the future scientific priorities for Australian astronomy, and recommends the investments, divestments and re-prioritisations required to realise these inspiring scientific goals. The highest priorities set out in this Decadal Plan suggest a funding profile for major optical/IR and radio astronomy facilities over the next decade. Existing funding for telescope access and operations of current facilities must be initially maintained, and then partly redirected to new facilities and augmented by new funding. Funding the skilled workforce to exploit this next generation of scientific infrastructure will require additional income from national competitive grant programs. Increasing astronomy competitive grant income by 20% is seen as an achievable goal.

10.1 Core facilities

Figure 10.1 illustrates the evolution of operations cost for Australian astronomy infrastructure under a scenario where core Australian optical/IR and radio astronomy capability is provided through the facilities of the SKA and ESO. For the reasons outlined in Section 7.1, including access to the broadest available instrument suite with which to address the scientific questions put forward in this Decadal Plan, membership of ESO would represent an excellent option for Australian access to 8-metre class optical/IR telescopes. In 2015, the estimated[1] joining fee for ESO is approximately $110M with an annual contribution of

1 Includes in-kind contributions capped at 25%.

$18M. Over the next decade, Australia's contribution[2] to complete SKA Phase-I will be approximately $130M. During SKA Phase-I construction, operations costs for the ASKAP telescope are estimated at $9M p.a., which will transition into the Australian share of operations costs for SKA Phase-I of $12–15M p.a. The roles of the AAO and ATNF will evolve towards support, training, and technology development for international observatories including ELTs and the SKA. Ongoing funding at the current level of approximately $15M p.a. will be required for these roles, in addition to telescope operation and astrophysics research costs.

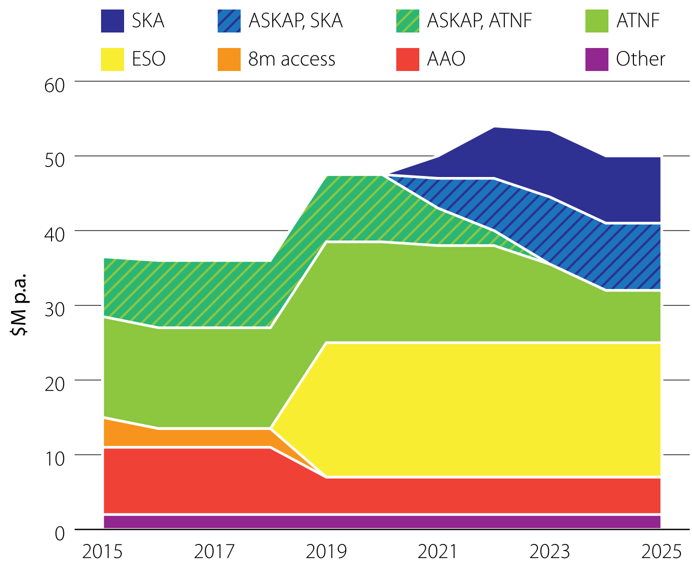
Averaged over the next decade, the combined operations cost of this core Australian astronomy infrastructure profile is approximately $46M p.a. The total capital investment required to transition to global facilities of ESO and the SKA during the next decade is approximately $240M. This represents a comparable capital investment in Australian astronomy to the investments made into the SKA precursor telescopes and the GMT during the previous decade. Australia will receive a significant return on investment through SKA operations and ESO instrumentation contracts. The international SKA contribution to running the SKA in Australia[3] will likely amount to an investment return of approximately $30M p.a., while ESO membership would return approximately $13M p.a. in instrumentation and industry contracts to Australia. Thus the increased operations cost for this profile relative to the past decade is offset by the economic and innovation investment returns provided through membership of the international ESO and SKA organisations. On the other hand, the opportunity to maximise benefit to the astronomy community and industry will decline if membership of ESO is left too late.

Because 8-metre class optical/IR telescopes will represent the 'workhorse' instruments of the next decade, it is fundamentally important that Australian astronomy have a long-term partnership in one of these facilities. While membership of ESO provides an excellent avenue to achieve this capability, this Decadal Plan also identifies an alternative strategy to seek membership of a state-of-the-art 8-metre class telescope with a 30% share. Partnership in a facility is crucial to enable long-term strategic planning in science programs, to influence the strategic direction of the facility, and to contribute to and

2 Assumes contribution to be 14%.

3 Assumes 40% of operating budget.

Figure 10.1: Core observatory operating costs over the decade (millions of FY15 dollars). Assumptions in this figure include i) the $4M p.a. cost for AAT running costs are provided as part of Australia's contribution to ESO; ii) the $15M p.a. cost for Parkes, ATCA, ASKAP is replaced by SKA; iii) operations funding for SKA commences four years prior to SKA science operations; iv) funding for Parkes and ATCA are redirected beginning two years prior to SKA science operations, while ensuring a sufficient overlap period for SKA key science projects; v) operations for ASKAP are assumed to be provided as part of Australia's contribution to SKA; vi) the 'other' line includes operations for smaller-scale national facilities including MWA and SkyMapper, and maintenance of data astronomical archives. ATNF and AAO costs exclude astronomy research, corporate overheads and depreciation.

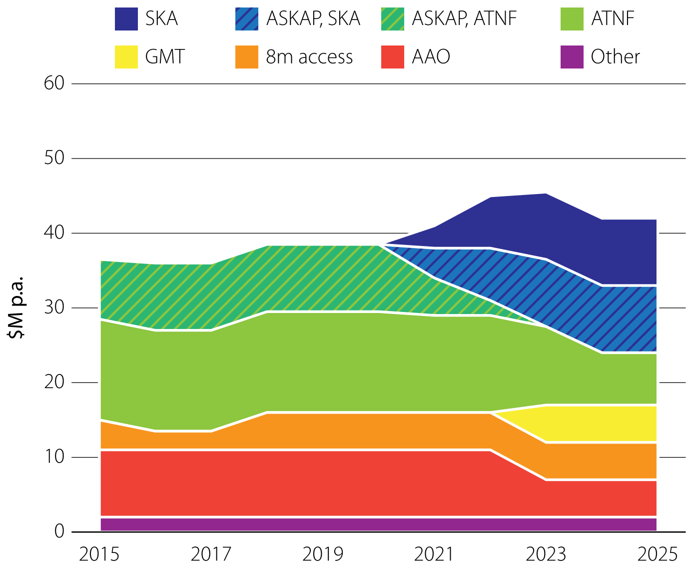


benefit from the technical development of key scientific instrumentation. The estimated cost[4] of such a partnership is $4.8M p.a., plus a $22.5M joining fee.

In this alternative operations scenario, which is illustrated in Figure 10.2, the Australian contribution to GMT operations (which includes new

4 The capital value of a state-of-the-art 8-metre class telescope is estimated to be $150M, with an annual operations cost of $16M. A 50% amortisation was assumed for joining an existing observatory.

Figure 10.2: Core observatory operating costs over the decade (millions of FY15 dollars) in the scenario where Australia does not become a member of ESO. Assumptions in this figure that replace the ESO operations in Figure 10.1 include i) Australia becomes a partner in an 8-metre class optical/IR observatory; ii) AAT ceases to be operated as a national facility towards the end of the decade; iii) upon its completion Australia contributes $5M p.a. towards operations of the GMT.



instrumentation development) is estimated to be $5M p.a. in order to maintain a 10% access share of an ELT. The total cost of this alternative strategy is $40M p.a. for operations costs across the Australian astronomy portfolio, with the total capital investment required to transition to this profile during the next decade of approximately $150M. Disadvantages of this alternative strategy with respect to membership of ESO include access to a significantly smaller suite of instrumentation and facilities for science, reduced access to ALMA, and loss of opportunities for industry engagement.

In the context of its key recommendations, this Decadal Plan emphasises the importance of partnership in an 8-metre class optical/IR telescope, relative to cost-per-night purchase of telescope capability. At the conclusion of the previous Decadal Plan period, Australian astronomers' national access to

8-metre class optical/IR telescopes was purely on a cost-per-night basis following the conclusion of Australia's role in the Gemini partnership. This cost-per-night purchase of telescope capability has facilitated excellent scientific programs from Australian astronomers that address the goals of the past Decadal Plan. However, continued cost-per-night purchase of telescope capability will not facilitate the opportunities for innovation and technology development that have kept Australian astronomy at the international forefront. Rather, long-term partnership is essential both to maintain scientific leadership and also for continued development of Australian astronomy in the ELT era. For these reasons it is recommended that the full goal of 30% of an 8-metre class optical/IR telescope (as opposed to a smaller fraction) should only be acquired on a cost-per-night basis where this funding does not come at the expense of innovative optical-IR telescope or instrumentation projects that include Australian innovation and leadership.

As Australian astronomical research infrastructure becomes increasingly global, the importance of stable, predictable, long-term infrastructure funding cannot be overemphasised. Although astronomy has been very well funded over the past decade, this funding has been unpredictable, and has increasingly been accompanied by short lead times and short funding horizons. The new generation of global astronomy facilities including the SKA and the GMT have development and construction periods of ~20 years, and operational lifetimes of at least 40 years. Thus, as Australian astronomy moves from domestically run observatories to large international and global facilities, a regular and predictable long-term funding system for major infrastructure will become increasingly important for effective strategic planning and international partner engagement.

10.2 Funding of mid-scale programs

During the past decade, new facilities and experiments that cost less than ~$1.5M were funded primarily through the ARC Linkage Infrastructure, Equipment and Facilities (LIEF) system. Facilities or upgrades with a cost of ~$10M or more were funded by national observatories and/or one of the major infrastructure grant schemes. A strategic approach to funding is required which is flexible enough to provide opportunities for unforeseen mid-scale investments on a competitive basis to allow scientists to conduct more ambitious experiments than possible through the ARC LIEF program. This


The High Energy Stereoscopic System (HESS) array including the central 28m telescope. CREDIT: C. MEDINA

> "A COMPETITIVE MID-SCALE PROGRAM IS THE MOST EFFICIENT AVENUE TO FACILITATE INNOVATIVE STRATEGIC INVESTMENTS"

Decadal Plan recommends that a competitive mid-scale program be implemented as part of an astronomy investment plan within national infrastructure funding, as the most efficient avenue to support strategic investments in new instrumentation for the next generation of telescopes, technology for emerging areas like gravitational wave astronomy, new instrumentation and operational costs of domestic facilities and international partnerships, and development of data archives to maximise scientific outcomes from astronomical data. The scale of such a program should be 10% to 15% of new infrastructure investment.

The impact of the GMT and the Advanced Instrumentation and Technology Centre

Australia has a long heritage of combining scientific and engineering excellence to design, manufacture and test the high precision instruments that support cutting-edge astronomical research.

The Australian Astronomy Decadal Plan of 2006 to 2015 identified the need for Australia to participate in a next-generation extremely large telescope (ELT) project thus implying the capacity to build commensurately larger instruments. The ANU's Advanced Instrumentation and Technology Centre (AITC) was established at

Mt Stromlo in 2006, helping to position Australia at the forefront of astronomical instrumentation development.

Projects underway to develop state-of-the-art astronomical instrumentation at the AITC include the GMT Integral Field Spectrometer (GMTIFS), a near-infrared imager and integral-field spectrograph. The total value for the design and build of this instrument to Australia is expected to be approximately $25M. Adaptive optics and instrumentation engineers are also designing the GMT Laser Tomography Adaptive Optics (LTAO) subsystem that will work in conjunction with GMTIFS to correct for the blurring caused by the Earth's atmosphere. The LTAO system will use six high-power lasers to generate artificial 'stars' in the sky and measure the turbulence in the atmosphere. In addition to refining the GMT LTAO system, this project has already developed capability in the use of adaptive optics for the tracking and de-orbiting of space debris that might cause damage to satellites. A third Australian contribution to the GMT is the AAO's MANIFEST, a fibre positioner designed to feed all the natural seeing spectrographs of the GMT. These and many other instrumentation projects support fundamental science research at multiple institutions and strengthen Australia's instrumentation capability. These projects are increasingly attracting industry partners and provide practical experience for students to strengthen Australia's capability. Since the AITC was first established in 2006 it has enabled instrumentation projects to the value of $117.8M including export contracts to the value of $18.4M.

The expansion of the AITC established a new national capability for the assembly, integration and test of large astronomical instrumentation, space systems and small satellites, including Australia's only Space Simulation Facility. The similarity between modern astronomical instrumentation and space-based systems, offered an opportunity to diversify and expand Australia's national capability in advanced manufacturing to the space industry. The new facilities, and an increased emphasis on developing Australian capability through industry-focused research and training, made it possible for the AITC to partner with and support the successful delivery of five Australian Space Research Program (ASRP) projects with a total value of $16.8M including: the Australian Plasma Thruster, the Automated Laser Tracking of Space Debris, Antarctic Broadband, Greenhouse Gas Monitor and GRACE Follow-on.

The emergence of the ANU AITC has expanded Australian industrial capability as well as enabling Australia to be a competent collaborator in an advanced manufacturing field previously limited to the leading industrialised nations. Australia's research and industrial toolbox is now much more sophisticated and capable.

Seeded by these activities, a Space Environment Management Cooperative Research Centre was established in 2014 to improve predictions of space debris orbits, and to

predict and monitor potential collisions in space. The centre builds on relationships and expertise developed through the Automated Laser Tracking of Space Debris ASRP project, and is made up of leaders from the space industry, academia and international agencies, including the ANU, RMIT, EOS Space Systems, Optus, Lockheed Martin, NASA Ames Research Center, and The Japanese National Institute of Information and Communications Technology. Expanding on this work EOS Space Systems, in partnership with ANU, were awarded a $6.4M commercial contract from the Korean Astronomy and Space Science Institute for a laser ranging telescope with adaptive optics. They also entered into a strategic cooperation agreement with Lockheed Martin in August 2014 to develop a new space object tracking site in Western Australia that will paint a more detailed picture of space debris for both government and commercial customers.

With the increased capability in Australia and the growth of the space market in the Asia Pacific region, a number of large multinational aerospace companies, including Lockheed Martin, Boeing, Northrop Grumman and MDA have increased their space presence in Australia. The AITC is already establishing links with research institutions and industry around the world and it has the potential to play an increased role in attracting opportunities to Australia.

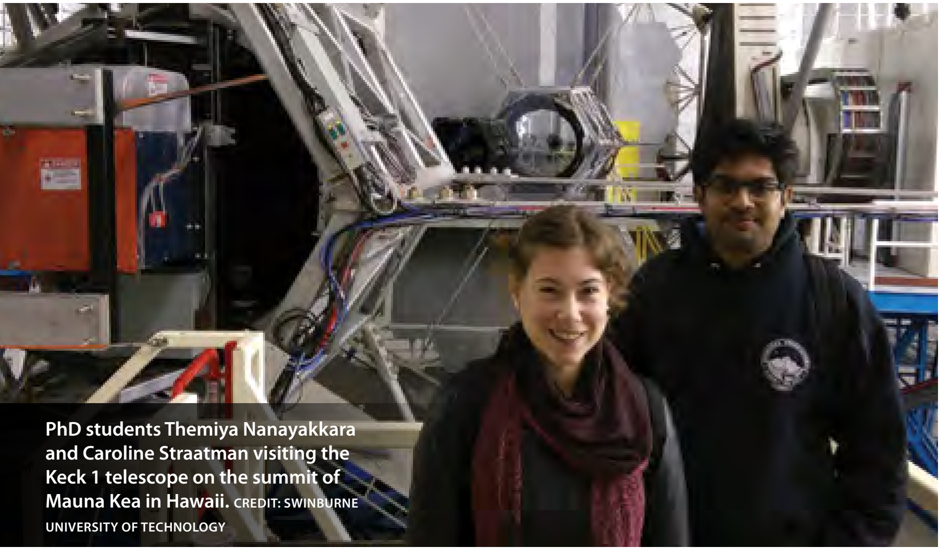
11 Australian astronomy 2016–2025

“ASTRONOMY IS ENTERING A NEW ERA OF EXPLORATION”

This Decadal Plan outlines the vision of Australian astronomers for their field in the coming decade. It describes the fundamental science questions that face astronomers in the quest to understand our Universe and our place within it, while positioning Australia to take advantage of future opportunities in the new era of large-scale international and global facilities. In the next decade, Australia must maintain its world-leading capability in the fundamental areas of optical/IR and radio observations and instrument building, which dominate the research impact of Australian observational astronomy. The Decadal Plan also highlights the very significant emerging strength of theoretical and computational astrophysics research within the overall national scientific capability.

This Decadal Plan identifies the following top-level scientific infrastructure priorities:

- Partnership equating to 30% of an 8-metre class optical/IR telescope. This is the critical unmet component of the astronomy capability portfolio, and is required to maintain Australia at the forefront of international astronomy. Excellent options for satisfying Australia’s optical/IR requirements would be provided by membership of ESO, or a partnership with another leading international observatory;
- Continued development and operations of the SKA precursors ASKAP and MWA at the Murchison Radio-astronomy Observatory, and membership of the SKA telescope;
- Partnership equating to 10% of a 30-metre class optical/IR extremely large telescope, such as the GMT;



PhD students Themiya Nanayakkara and Caroline Straatman visiting the Keck 1 telescope on the summit of Mauna Kea in Hawaii. CREDIT: SWINBURNE UNIVERSITY OF TECHNOLOGY

- Capability within the national observatories AAO and ATNF to maximise Australia's engagement in global projects through instrumentation development for these and other observatories, and to manage and facilitate Australian engagement in international telescope projects;
- World-class high performance computing and software capability for large theoretical simulations, and resources to enable processing and delivery of large data sets from these facilities.

In pursuing its scientific agenda this Decadal Plan identifies four priorities for increasing the engagement and broader impact of the Australian astronomy community:

- Utilisation of astronomy to help improve the participation and standard of science education in schools through teacher-training programs;
- Provision of graduate and postgraduate training that includes transferable skills to provide highly valued graduates for roles in wider society;
- Establishment of a central body to promote and facilitate industry engagement, ensuring that Australian industry benefits from opportunities facilitated by the next generation of global facilities, and to maximise the flow of innovative technologies from fundamental research into commercial application;

- Adoption of principles and practices that achieve at least 33% female representation at all levels of Australian astronomy by 2025 in alignment with the current PhD student cohort.

The coming decade will see a shift in the 'workhorse' facilities of Australian astronomy away from domestically built and operated telescopes towards international telescopes run by global collaborations. The engagement of Australian industry will become increasingly important for the construction of these large telescopes and their instrumentation suites, which present significant opportunities for economic returns to Australia. At the end of the next decade, the roles of the AAO and ATNF will evolve from operating Australian-based national facilities to managing Australia's partnership in international facilities, operating those facilities where they are based in Australia, supporting Australian users, and running critical instrumentation development programs. The Decadal Plan anticipates that facilities such as the AAT, the Parkes telescope and the ATCA may no longer be operated as national facilities by 2025 when their scientific capabilities are increasingly superseded by the next generation of optical/IR and radio telescopes.

Beyond the traditional strengths of Australian astronomy, a revolution is expected during this Decadal Plan period following the detection of gravitational waves, which, along with next-generation high-energy telescopes and Antarctic astronomy, will open new windows to astrophysics. Mid-scale investment in large international facilities will provide the tools for Australian discoveries in these areas.

By 2025, this Decadal Plan aims to have positioned Australia to take full advantage of its host role in the international SKA, with expertise built through the operation of precursor telescopes ASKAP and MWA on the Murchison Radio-astronomy Observatory. Australian optical/IR astronomers will benefit from the early investment in the GMT project using knowledge built through long-term access to 8-metre class telescopes. A stable partnership in an 8-metre class optical/IR telescope will facilitate Australian leadership of the scientific direction of such facilities, driven by its world-leading astronomers and the innovative instrumentation technologies for which Australia is known. The next generation of telescopes will spark an explosion of discovery, enabling exploration beyond the horizons set by the previous Decadal Plan.

Abbreviations

AAL	Astronomy Australia Ltd
AAO	Australian Astronomical Observatory
AAT	Anglo-Australian Telescope
ALMA	Atacama Large Millimeter/submillimeter Array
ANU	Australian National University
ARC	Australian Research Council
ASKAP	Australian SKA Pathfinder telescope
ATCA	Australia Telescope Compact Array
ATNF	Australia Telescope National Facility
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EIF	Education Investment Fund
ELT	extremely large telescope
ESO	European Southern Observatory
FTE	full-time equivalent
GMT	Giant Magellan Telescope
HPC	high performance computing
IR	infrared
LIEF	Linkage Infrastructure, Equipment and Facilities
MRO	Murchison Radio-astronomy Observatory
MWA	Murchison Widefield Array
NASA	National Aeronautics and Space Administration (USA)
OECD	Organisation for Economic Cooperation and Development
p.a.	per annum
SKA	Square Kilometre Array
STEM	Science, Technology, Engineering and Mathematics

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WG 1.2 **Stars and planets** Chair: Dr Michael Ireland

WG 1.3 **The galaxy** Chairs: Dr Jill Rathborne and Professor Naomi McClure-Griffiths

WG 1.4 **High energy and fundamental astrophysics** Chair: Dr Duncan Galloway

WG 2.1 **International scale facilities** Chair: Professor Karl Glazebrook

WG 2.2 **Local and institutional scale facilities** Chair: Dr Kate Brooks

WG 2.3 **eScience** Chair: Dr Darren Croton

WG 3.1 **Demographics** Chair: Professor Sarah Maddison

WG 3.2 **Education, training and careers**
Chairs: Dr Amanda Bauer and Associate Professor John O'Byrne

WG 3.3 **Industry** Chair: Professor Carole Jackson

WG 3.4 **Research funding** Chair: Professor Chris Tinney

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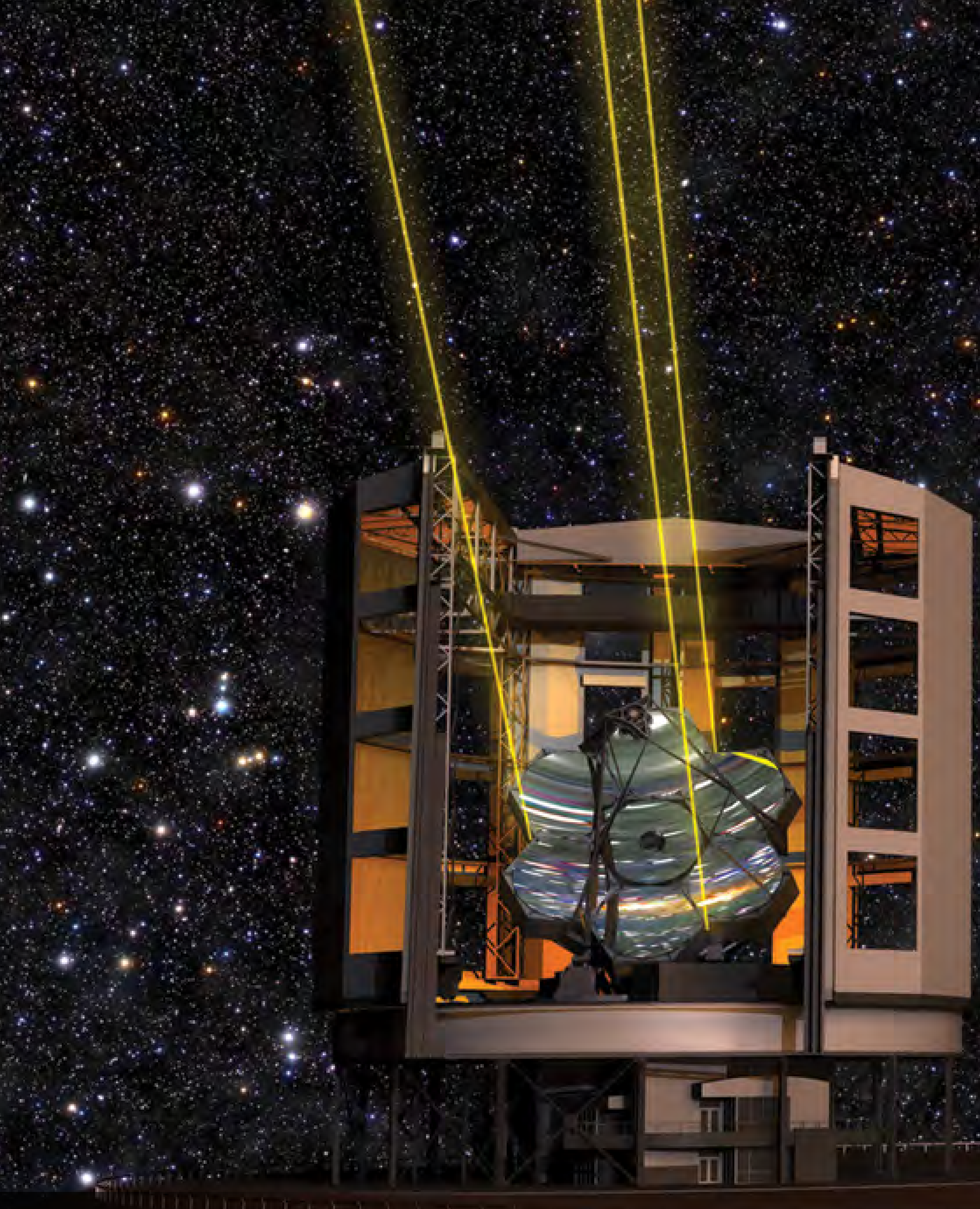

Artists conception of the Giant Magellan Telescope facility during Laser Tomography Adaptive Optics observations. CREDIT: GMTO CORPORATION