Australian Academy of Science

Mid-Term Review

of the Australian Astronomy Decadal Plan 2006–2015

Prepared by the National Committee for Astronomy of the **Australian Academy of Science** July 2011

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of the Australian
Astronomy Decadal Plan
2006–2015

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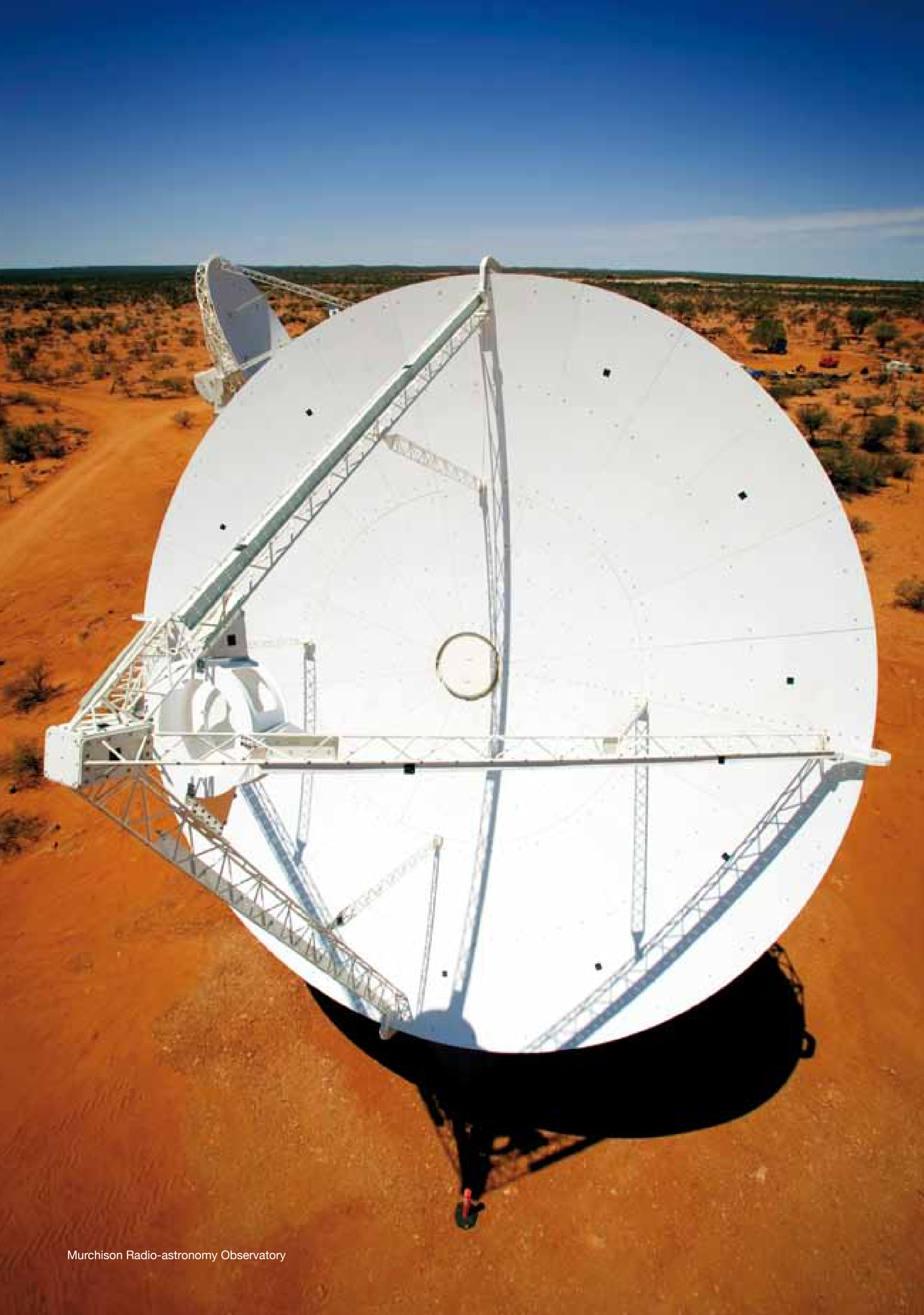

Murchison Radio-astronomy Observatory

Executive Summary

Australian astronomy is riding a wave of discovery powered by new technology. This technology has increased the sensitivity of existing telescopes and enabled the construction of new telescopes that can see wider and further than ever before. Australian facilities are finding planets around other stars and seeing the explosions of the first stars in the Universe 13.2 billion years ago. These discoveries help us understand humankind's place in the Universe; they also stimulate our capacity for innovation in science and engineering, and inspire and educate future generations of scientists, engineers, and technologists.

In *New Horizons: A Decadal Plan for Australian Astronomy 2006–2015*, the Australian astronomical community presented a strategic vision for its continued engagement in this exciting enterprise – a vision of a structured pyramid of investment in people and facilities. The Decadal Plan looked to the future, proposing early engagement in the next generation of facilities while reinforcing the foundations of our current research capability. The plan included achieving a 10 per cent participation in the development of both the Square Kilometre Array (SKA) and an Extremely Large Telescope (ELT), securing a 20 per cent share of an 8-metre optical telescope, continuing development of astronomy in Antarctica and supporting our existing national facilities, the Anglo-Australian Observatory, and the Australia Telescope National Facility, through revamped operational models. The Decadal Plan also proposed a peak body to help coordinate Australia's astronomical activities, a goal that has been realised with the formation of Astronomy Australia Limited in 2007.

This Mid-Term Review reaffirms the key goals of the Decadal Plan. It acknowledges both the Government's significant investment in astronomy facilities over the past five years and its recognition of astronomy as a flagship Super Science area.

Major new funding has been allocated for astronomy infrastructure in Western Australia, including construction of the Australian Square Kilometre Array Pathfinder (ASKAP) and the Pawsey High-Performance Computing Centre for SKA Science. In New South Wales, the Australia Telescope has been upgraded with a new array of receivers, dramatically improving its sensitivity. Technical advances in antenna and receiver design, enabled by the pathfinder telescopes at the Murchison Radio Observatory, represent crucial steps toward the final design of the SKA.

Australia has become a partner in an ELT program through co-investment by Astronomy Australia Limited with the Australian National University in the Giant Magellan Telescope. This ELT is being built in Chile by a consortium of international partners and Australia's investment has secured a 10 per cent share in the telescope's capital. In 2010, the Anglo-Australian Observatory became a wholly Australian entity, the Australian Astronomical Observatory, and has been placed on a secure financial footing as a division of the Department of Innovation, Industry, Science and Research.

While the current investment in astronomy infrastructure has created tremendous opportunities, and positioned Australia well for the years ahead, there are also some significant challenges. This Mid-Term Review sets out the priorities of the Australian astronomy community for the second half of the 2006–2015 Decadal Plan period in light of these successes and challenges.

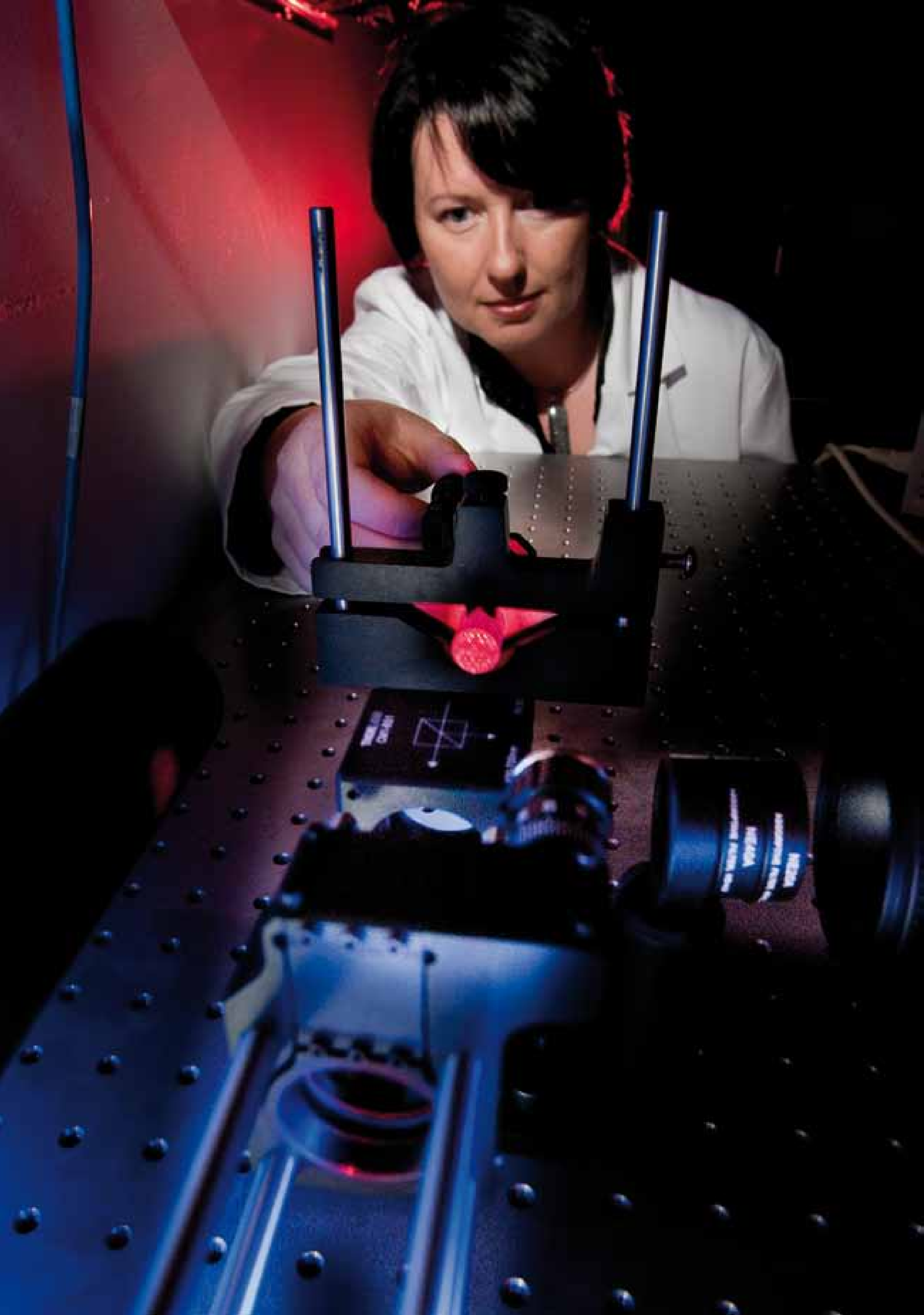
The astronomical community must ensure that Australia is in the best possible position to participate in and host the international SKA. This includes continued development and operations of ASKAP, protection of the radio quiet zone in Murchison, Western Australia, and a re-baselined operation of the existing national facilities for radio astronomy.

Australian astronomy needs to secure long-term access to a portfolio of astronomical facilities including access to 20 per cent of an 8-metre telescope. The community believes this is best done via membership in the European Southern Observatory (ESO), but it could be alternatively pursued through a revitalised partnership with the Gemini and/or Magellan telescopes coupled to a long-term investment plan for operational and capital expenditure on next-generation facilities. The Australian Astronomical Observatory will undertake a review to determine how it can best support the future portfolio of optical astronomy facilities.

Australian astronomy also benefits enormously from the breadth of astronomical discovery through investment in the areas of theoretical astrophysics, Antarctic astronomy and ground-based high-energy astrophysics, as well as through university-based research facilities. It is important that funding programs remain in place to support this scale of investment.

Over the past five years and within the framework set out in its Decadal Plan, Australian astronomy has continued its proud record of outstanding achievement. In the next five years the community aims to build on Australia's current high standing in world astronomy, ensuring that the new research facilities funded during 2006–2011 are scientifically productive at the highest international level, enabling fundamental discoveries about the Cosmos.

ASKAP antennas



Australian Astronomy 2006–2010

We are now midway through the period covered by *New Horizons: A Decadal Plan for Australian Astronomy 2006–2015*, and it is timely to review the successes achieved and challenges remaining for the astronomy community in light of the strategic vision set out in the Decadal Plan[1].

Astronomy in Australia encompasses the study of a wide range of physical phenomena in space and time, from cosmology and the early Universe to the formation and evolution of galaxies, the discovery of new planets and solar systems and the internal workings of their parent stars. Recent advances in telescopes and instrumentation have made astronomy one of the most data-rich sciences, leading to the adoption of advanced technologies in high performance computing and data storage. Astronomers are active in the online eResearch sphere, developing new ways to interact with, exploit and share their data.

The last five years have been extremely successful for the Australian astronomy community, with astronomy recognised as a flagship Super Science by the Australian Government and significant financial investment for new facilities.

As part of Australia's bid to host the international Square Kilometre Array (SKA)[2], the Australian SKA Pathfinder (ASKAP) is being constructed in Western Australia. ASKAP will revolutionise our understanding of astrophysical phenomena, including the growth of galaxies from cosmic hydrogen, the extreme physics of neutron stars and black holes, and the evolution of the large-scale magnetic fields threading the Universe. To process the torrent of new data from ASKAP, a new supercomputer facility, the Pawsey High-Performance Computing Centre for SKA Science (Pawsey Centre), is being built in Perth. When this reaches its full configuration in 2013, it is expected to be one of the top ten most powerful computers in the world.

The Australian Government has invested strongly in Australian astronomy since 2005, with much of this going toward the ASKAP radio telescope, the Pawsey Centre and Australia's membership in the Giant Magellan Telescope. In addition, the Australian Astronomical Observatory has achieved security of funding until at least 2018. There have also been significant contributions from state governments, as well as university investment in new facilities like the SkyMapper telescope at the Australian National University.

Most of this funding, however, is for infrastructure only; personnel and operational costs must be sought elsewhere and can total many millions of dollars per year. *In the coming years, ongoing operational funding for our research facilities will remain a significant challenge; one that must be addressed in order to realise their full potential.*

The two national observatories have undergone some changes since 2005. The Australia Telescope National Facility (ATNF) merged into the new CSIRO Division of Astronomy and Space Science (CASS) in 2009, and the Anglo-Australian Observatory transitioned from a joint UK and Australian facility to a wholly Australian entity, the Australian Astronomical Observatory (AAO), in June 2010.

A significant advance since 2005 is the establishment of Astronomy Australia Limited (AAL), a not-for-profit company limited by guarantee, whose members are Australian universities and research organisations. AAL manages programs which provide astronomers with access to national optical/infrared and radio astronomy infrastructure, and which are not directly funded by the two national observatories. It was set up in 2007 to manage the $45 million provided for astronomy facilities through the National Collaborative Research Infrastructure Strategy (NCRIS), but has since taken on the management of additional funds provided through the Education Infrastructure Fund (EIF) and other sources.

Australian astronomy recently gained a new Australian Research Council (ARC) centre of excellence, the Centre of Excellence for All-Sky Astrophysics (CAASTRO). CAASTRO will inject a total of $29 million into the astronomy community over the next seven years, which will support postdoctoral researchers and PhD students working on science projects with national and international research facilities. When funding for Super Science Fellows and CAASTRO is added to past successful ARC Discovery Project grants, financial support for researchers has steadily increased since 2005 (in 2005 dollars), a positive sign.

Alongside the new investment in facilities, the astronomical community in Australia is growing. The number of active astronomers working in Australia has increased by more than 20 per cent over the past five years, mainly through a rise in PhD student numbers and fixed-term research positions. Australian astronomy remains diverse, with the numbers of researchers, by sub-field, nearly equally split between radio, optical, and theory.

Australia's investment in astronomy has translated into world-leading science, and subsequent national and international recognition. Australian astronomers have been awarded some of the most prestigious national and international research prizes, including the 2006 Malcolm McIntosh Prize for Physical Scientist of the Year, the 2006 Shaw Prize, the 2007 and 2009 Gruber Prize, the 2007 and 2009 L'Oreal Australia For Women In Science Fellowships, the 2009 Prime Minister's Prize for Science, and the 2009 and 2011 Pawsey Medals.

AAT mirror cell

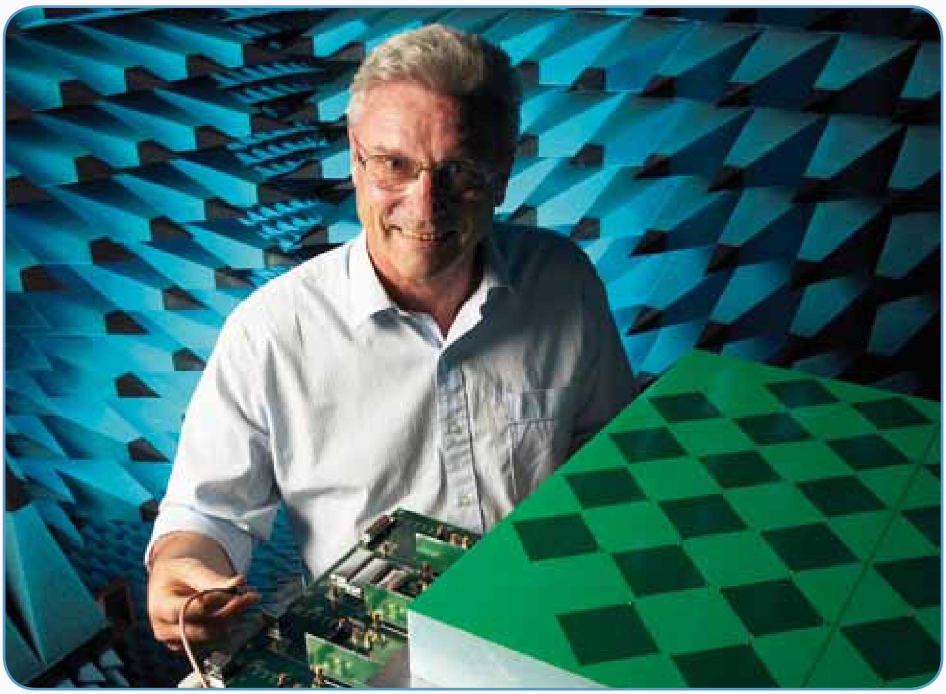
Connecting the world through radio waves

Where would we be without WiFi? Wireless communication systems are found in laptop computers, phones and an ever-increasing number of other electronic devices. About 1 billion of these devices are used worldwide every day in airports, universities, cafes, homes – anywhere there's a hotspot. The wireless local area network technology that allows us to remotely connect to the internet or network with other computers came out of pioneering work in radio astronomy.

Back in the 1970s, Dr John O'Sullivan FAA was part of a team trying to detect radio pulses from exploding mini black holes. They had to search through vast quantities of film looking for a short time event. To do this they used an optical Fourier transform device. This cleaned up the data, which becomes distorted on its trip through the atmosphere, and gave them a sharper, clearer picture. In turn, it also initiated an examination of digital implementations via Fast Fourier transform and detection techniques to allow much more effective searches.

Nearly twenty years later, John and his small CSIRO Radiophysics team were working on signal processing and wireless communication. They recognised that the earlier radio astronomy work could be applied here, too, and used a related technique to reduce the multipath interference of radio signals transmitted for computer networking. This solved the problem of transmitting wireless data indoors at high data rates. CSIRO's invention was granted a US patent in 1996 and holds corresponding patents in 18 countries. It is a core technology for WiFi implementation.

John was awarded the Prime Minister's Prize for Science in 2009 for his achievements in astronomy and wireless technology. He is a digital systems engineer at CSIRO's Division of Astronomy and Space Science and is currently working on the development of an innovative radio camera for the Australian Square Kilometre Array Pathfinder radio telescope.



John O'Sullivan

Decadal Plan Goals and Progress

During the 2006–2011 time period, Australian astronomy has continued its strong track record of discoveries and enhanced our understanding of the Universe. In addition, the community has continued to engage with and contribute to global projects and collaboration.

The 2006–2015 Decadal Plan goals, progress and challenges are summarised here for the areas of radio and millimetre astronomy, optical astronomy, theoretical astrophysics, high-performance computing and Antarctic astronomy, as well as the newer fields of ground-based high-energy astrophysics and gravitational-wave astronomy.

Radio and Millimetre Astronomy

Decadal Plan goals

The key recommendations of the Decadal Plan in the area of radio astronomy are:

> *The development of new radio astronomy infrastructure in Western Australia, leading to the start of construction of the SKA Phase 1 at the end of this decade, will be an effective way for Australia to engage in the SKA at the 10% level.* (Decadal Plan page iv)
>
> *Continued operational support for the existing ATNF telescopes (Parkes, Mopra and Compact Array) is seen as important throughout the next decade. Nevertheless, over this period, resources from these telescopes will increasingly have to be reprioritised into the development and operation of infrastructure on the roadmap to the SKA if Australia is to maintain its world-leading position in radio astronomy.* (Decadal Plan page 31)

Progress against the Decadal Plan

An impressive amount of new funding has been allocated for astronomy infrastructure in Western Australia, including construction of the Australian Square Kilometre Array Pathfinder (ASKAP), the Pawsey Centre and Sustainable Energy projects. Funding for the International Centre for Radio Astronomy Research (ICRAR), the Australian Research Council (ARC) Centre of Excellence for All-Sky Astrophysics (CAASTRO) and ARC Super Science Fellowships has seen a corresponding growth in Australia's radio astronomy research capacity.

Technical advances in antenna and receiver design enabled by the technology and science pathfinder telescopes at the Murchison Radio Observatory represent crucial steps toward the final design of the Square Kilometre Array (SKA). The wide-field ASKAP and Murchison Widefield Array (MWA) will be the most powerful radio telescopes in the world for surveys in their respective frequency bands.

The Gemini North telescope

A strong team of researchers has already been formed to design and carry out the ASKAP science program. The collaborators on ASKAP survey projects represent all nations with radio astronomy aspirations, and include over 350 participating scientists from 161 institutions worldwide. Further expansion of international collaboration based around these telescopes is a highly productive way to leverage Australia's investment in the technical development needed for the full SKA.

The MWA will search for the earliest traces of atomic hydrogen in the Universe, before the first stars and galaxies formed, and is making important advances in low-frequency astronomy. Continuing construction and development of the MWA is part of the path toward SKA Phase 1 (SKA1), the first stage of construction of the full facility.

Alongside these new facilities, the existing national radio observatories continue to be successful and highly productive. These observatories will follow up ASKAP and MWA discoveries, as well as making further discoveries on their own. CSIRO has already made substantial cost savings in the operations of these telescopes, and further savings are envisaged through initiatives such as the Science Operations Centre. Due to the scale of the investment in ASKAP, continued operation of the existing ATNF facilities even at a reduced scale will require an increase in the overall operations budget for the CSIRO Division of Astronomy and Space Science (CASS).

In addition to the MWA, which is being built by a consortium of Australian and US universities, existing university radio facilities continue to play an important role in technology development and student training, as well as carrying out research programs. For example, since completing the 843 MHz Sydney University Molonglo Sky Survey (SUMSS) in 2007, the University of Sydney's Molonglo radio telescope has been upgraded with a prototype state-of-the art wide-band spectral-line correlator. In addition, the University of Tasmania has taken the national lead in operating a suite of telescopes for long-baseline radio interferometry, a capability being upgraded starting in 2007, to enhance its Geodesy capability, through the NCRIS company, AuScope.

The international landscape for radio astronomy

SKA1, followed by the SKA itself, remain the ultimate goals for radio astronomy in the coming decade. The path to the SKA has always been a complex international one with many new radio facilities currently coming on-line. These include:

- the upgraded mid-frequency US National Radio Astronomy Observatory's Expanded Very Large Array (EVLA)
- the Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility which is a partnership of countries from Europe, North America and East Asia in cooperation with the Republic of Chile
- two major new Dutch facilities, the Low-Frequency Array (LOFAR) and the Apertif wide-field upgrade to the Westerbork Synthesis Radio Telescope
- MeerKAT, the South African SKA precursor array
- eMERLIN, a recently-upgraded long-baseline array in the UK.

ALMA, currently under construction in Chile, will be the first truly global facility for radio astronomy. It will come into full operation in 2013, with early science data starting to flow in 2011. Australia is not currently a member of the ALMA partnership, but continues to invest in pathways that will enable Australian astronomers to be involved with ALMA data at a modest level, such as the joint fellowship programs shared between the University of Chile, CSIRO and the University of New South Wales.

Global engagement with the SKA is strong, but in some parts of the world this engagement is moderated by the current realities of science funding and recent priority setting.

For example, *Astro2010*, the recent US Decadal Survey demonstrated that, in the US at least, the highest priority ground-based astronomy initiatives to be considered are the Large Synoptic Survey Telescope, a mid-scale innovation program (including the Hydrogen Epoch of Reionization Array (HERA), a large-scale low-frequency radio telescope on the path to the SKA), and a 20–30-metre class optical telescope.

In Europe, the SKA and the European-Extremely Large Telescope (E-ELT) were rated as equal top-priority projects, with the recognition that large-scale funding for the full SKA would not be available until after E-ELT construction. This sequencing does not preclude strong European engagement in the global SKA research and development program and the design and construction of SKA1.

Funding for the four-year detailed design phase of SKA1 is expected to become available in 2012. This will see strong collaboration between Australian institutions and global partners in an intense research and development program. A major challenge is to convince our potential funding partners that Australia is the best site for the SKA. Australia should continue to promote the clear technical quality of the core site, the ease with which long baselines can be deployed, the necessary political stability and security to operate a facility over many decades, and the existence of a strong, knowledgeable community to assist in the support and use of the SKA.

The period 2011–2015 and beyond

Australian radio astronomy is in a strong position, but there are issues which need to be addressed in the next five years.

Continuing along the pathway to the SKA

Priority should be given to demonstrating the scientific quality of the Australian site, and its associated radio-quiet zone. This involves early observations with prototype versions of ASKAP and the MWA. These pathfinder telescopes will demonstrate the world-class nature of the Western Australia site, and are also world-class research facilities in their own right. The best outcome for Australian researchers wishing to lead future SKA projects is for these facilities to be completed on time and for the planned surveys to begin their task of making ground-breaking advances in astronomy.

Australia's participation in the SKA should not be conditional on hosting the facility. Wherever it is sited, Australian expertise will be needed to help build the SKA and researchers in Australia will be competitive in winning time and leading SKA science projects. It is important that appropriate resources to support SKA science (eg a science centre) are available in Australia, irrespective of the telescope's location.

Radio astronomy has always had strong links to industry in Australia with the connection working in both directions. The delivery of intellectual property (IP) to industry is exemplified most powerfully through the well-known story of the 802.11 WiFi protocol (see Box on page 7). This continues with the more recent licensing of active stretch-forming in antenna manufacture, developed as a result of ASKAP construction, which may have relevance in aircraft manufacture; and CSIRO's work with Siliana and its silicon-on-sapphire technology for a receiver-on-a-chip project, which may have relevance to the defence and telecommunications industries. In addition, CSIRO is exploring the use of phased-array feeds in medical imaging and other applications.

ASKAP, the radio-astronomy infrastructure at the Murchison Radio-astronomy Observatory (MRO) and the construction of the Pawsey High Performance Computing Centre for SKA Science (Pawsey Centre) in Perth will benefit from access to sustainable energy investments, through geothermal sources at both the MRO and Pawsey Centre and through the use of solar power as a contribution to the power solution for ASKAP. The presence of ASKAP and the MWA on the Murchison site, and the need for high-bandwidth connectivity from these telescopes to the Pawsey Centre was a factor in the rapid delivery of the recently completed Perth-Geraldton link, one of the first steps towards the National Broadband Network.

Finally, as we look forward to the design phase of the SKA, Australia will be able to take advantage of the Australasian SKA Industry Consortium, a group of 24 companies, many of them global household names, who are familiar with the SKA, are involved in several aspects of the design and are keen to become more heavily engaged as the SKA project proceeds further.

Future support of national facilities

Access to the existing national radio-astronomy facilities run by CSIRO will remain important for the remainder of the Decadal Plan period; although the community needs to prepare for decreased support of these instruments as operations funding is channeled into ASKAP.

The issue of operating expenses will also arise for the MWA, owing to significant fuel, computing and travel costs, although its operating model is likely to be cheaper than that of ASKAP. With the end of NCRIS in 2011, there is currently no obvious funding channel in Australia for MWA operations.

ALMA engagement

In the decade before the SKA construction is complete, ALMA will produce a wealth of scientific discovery. With their continued use of Mopra and the Australia Telescope Compact Array as ‘finder’ instruments for Galactic and Magellanic science, Australian astronomers are in a great position to ‘punch above their weight’ in the early days of ALMA. Through collaboration with investigators from ALMA-member countries, the community can engage in important new research topics with relatively small levels of investment (eg travel costs, workshops, continuation of joint fellowship programs underway between Australian and Chilean institutions and perhaps a small science centre).

Membership in the European Southern Observatory (ESO) would give Australia direct participation in ALMA, enabling Australian astronomers to influence the strategic direction of the observatory and participate in instrument upgrades for the telescope. The Australian astronomy community prioritised the SKA ahead of ALMA in the Decadal Plan, but being part of ALMA through ESO would allow Australia to participate more actively in this first of ground-based astronomy’s billion dollar facilities.

Naomi McClure-Griffiths

Many of astronomy's key science questions will best be answered by using ALMA's unique capabilities in conjunction with our new radio and optical facilities.

Key recommendations

- Australia must ensure that it remains in the best possible position to participate in and host the international SKA. Important activities to support this cause include:
  - continued development of SKA pathfinders on the Murchison site, provision for their operational costs, and support of their data-processing and analysis requirements by the Pawsey Centre
  - long-term protection of the radio-quiet zone in Western Australia. CSIRO should continue an active engagement with the Federal and Western Australia Governments to secure and maintain this protection
  - Australian engagement with the European, US, and emerging radio-astronomy communities in India and China over the next five years to secure and develop the first phase of the SKA. This engagement should seek to embrace new initiatives, such as the proposed US HERA, utilising CSIRO's engineering and technical expertise and the growing scientific and technical collaborations built around ASKAP and the MWA.
- CSIRO should carry out a review and priority-setting exercise, in consultation with the community, to assess how CASS can most effectively transition its current funding stream and existing national radio facilities to support current research programs and future programs enabled by its new facilities.
- Engagement with ALMA, through cost-effective support of initiatives that leverage existing research expertise and complementary existing facilities, should be pursued, until ESO membership is secured.

Understanding our Galactic home

What do the Milky Way Galaxy and a soft-bodied marine cephalopod have in common? They both have several 'arms' that curve out from their centres – hence Dr Naomi McClure-Griffiths' description of our Galaxy as a 'cosmic octopus'!

Naomi is an OCE Science Leader at CSIRO Astronomy and Space Science and an Adjunct Professor at the University of Sydney; she is also an internationally recognised expert on the Milky Way. Her main research focus is to better understand the structure and evolution of our Galaxy. It is a challenging task and she says, "Studying the shape of the Galaxy from Earth is like an ant studying Sydney from a suburban garden in Penrith". But this hasn't stopped her – in the past few years her studies have led to the discovery of a new spiral arm and changed many long-held ideas about how our Galaxy has changed over time.

In her research Naomi uses radio telescopes to look at the interstellar medium, the dust and gas between stars. She is the Principal Investigator on the Galactic All Sky Survey, which used the CSIRO Parkes radio telescope to create the most sensitive and high resolution all-sky atlas of hydrogen. To create the atlas, Naomi and the team spent 2,500 hours in the telescope over two years. She is now co-leading the Galactic Australian SKA Pathfinder Survey to study the evolution of gas in the Milky Way.

In 2006 Naomi was awarded the prestigious Malcolm McIntosh Prize for Physical Scientist of the Year for her insight into the structure of our Galaxy and her research leadership.

Optical/Infrared Astronomy

Decadal Plan goals

Optical astronomy is a cornerstone of humanity's investigations of the Universe, near and far, and a vital component of Australian astronomy's outstanding international reputation – with half of our international scientific impact due to optical facilities[3]. The Decadal Plan prioritised a tiered investment in optical infrastructure based around a hierarchy of increasingly large telescopes. These included fully supporting the 4-metre Anglo-Australian Telescope and Observatory through to 2018, providing the equivalent of 20 per cent access to an 8-metre class telescope, and supporting investment at a 10 per cent level in an Extremely Large Telescope (ELT) program.

Progress against the Decadal Plan

Significant progress was made against the Decadal Plan's goals for optical astronomy over the past five years. On 1 July 2010, the Anglo-Australian Observatory transitioned to become the Australian Astronomical Observatory (AAO), and has achieved security of funding until at least 2018. The AAO has also received NCRIS funding for the HERMES instrument (the primary instrument upgrade intended to maintain the scientific impact of the AAO as envisaged in the Decadal Plan).

Australia has maintained its world leadership in the development of innovative technologies in optical and infrared astronomy. The Research School of Astronomy and Astrophysics of the Australian National University delivered its second instrument, GSAOI, to Gemini on time and on budget. AAO, with partners at the University of Sydney and Macquarie University, has pioneered new techniques in astrophotonics, a field that has largely grown up in Australia through synergistic research with the telecommunications industry. These developments have led to several international patents, which are being exploited by local industry, including the development of a revolutionary micro-spectrograph for the medical industry.

Australia has also become a partner in an ELT program. Through its strategic options process, Astronomy Australia Limited (AAL) (on behalf of the Australian astronomy community and NCRIS) co-invested approximately $4 million in the Giant Magellan Telescope (GMT) with the Australian National University. This secured a 10 per cent share of the telescope's Design Development Phase.

This initial investment was followed in 2009 by an $88 million Education Investment Fund Grant to the Australian National University. This grant included $65 million for telescope capital payments to the GMT project office 2010–2014, $16.5 million for Australian instrumentation project support, and $6.5 million for an upgrade to the Advanced Instrumentation and Technology Centre building at Mt Stromlo. The Education Investment Fund capital investment in the telescope is split as a 50:50 partnership between the Australian National University and AAL.

As of 2011, the GMT project has secured approximately 40 per cent of the funds needed for the currently costed capital build-out, with committed partners, in addition to Australia, being Korea, the Carnegie Institution, and the University of Chicago. Harvard University, the Smithsonian Institution, the University of Texas, Texas A&M, and the University of Arizona all remain active partners, although it is unclear on what time scale these institutions are likely to raise their fraction of capital.

As with all ELT projects, there is significant risk associated with the GMT. The prospects for raising the remaining capital for the telescope are unclear, and the US National Science Foundation has been directed by the US Decadal Survey to choose between one of the two competing telescope projects. The GMT program in Australia is developing close working ties with local industry to develop adaptive optics technologies with the potential for both astronomical and commercial exploitation. These technical developments are relevant to all the currently planned ELTs.

Involvement in 8-metre class telescopes, the current top tier of optical facilities, has fallen short of the Decadal Plan goal over the past five years. In today's world, 8-metre telescopes are the most productive sector of astronomical facilities and are at the core of any world-class astronomical program. For the last several years, Australian astronomers have had access equivalent to a 16.5 per cent share in an 8-metre class telescope via our membership in Gemini, and through the purchase of Magellan nights by AAL (partially funded by NCRIS). As part of these arrangements, Australia took a leading interest in the Wide-Field Multi-Object Spectrograph, an instrument for Gemini which would provide an unprecedented ability for spectroscopic mapping of the heavens. In 2009, due to financial constraints, the Wide-Field Multi-Object Spectrograph project was cancelled after six years of planning, leaving the existing and future Gemini instrumentation suite imperfectly aligned with Australia's research interests. In addition, the long-term funding for 8-metre telescope access is not yet secure, leading to the highly undesirable situation of potentially having little or no 8-metre telescope time for our research community in the future.

Optical infrastructure has also seen some key developments at the university level. These include the completion of the Australian National University's SkyMapper telescope and WiFES spectrograph for the 2.3-metre telescope, the completion and plans for several new small- to medium-sized telescopes at Siding Spring Observatory, plans for a new 1.3-metre telescope in Tasmania, and the completion of the University of Western Australia's 1.0-metre Zadko telescope. In addition to undertaking specific internationally competitive projects, these facilities serve as gateways to Australia's highest levels of astronomical infrastructure, and serve essential roles in our training of young scientists.

The period 2011–2015 and beyond

The transition of the Anglo-Australian Observatory into the Australian Astronomical Observatory has secured the 4-metre tier in Australia's optical astronomy telescope hierarchy for the coming decade. The top of the hierarchy, involvement in a next generation ELT, has also been strongly supported in the form of full funding of Australian participation at a 10 per cent level of the GMT. The delivery of funding for these two facilities has gone beyond what was envisioned in the Decadal Plan, but has left a hole in the middle – long-term 8-metre telescope access.

From 2013, our community faces reduced 8-metre telescope access, leaving an imbalance in our astronomical portfolio. This shortfall has the potential to undermine the already committed large-scale investment in our astronomical infrastructure including the Anglo-Australian Telescope (AAT), ASKAP, and the GMT. To rectify the current imbalance, funding needs to be obtained to achieve a 20 per cent share of an 8-metre class facility.

An external review of Australia's NCRIS program options for optical-infrared astronomy by some of the world's most pre-eminent astronomers (the Astronomy NCRIS Strategic Options Committee or ANSOC), commented that:

> *8-metre class telescopes will remain the premier ground-based research facilities in optical-infrared astronomy for at least the next decade and will play a central role in the subsequent ELT era, and Access to these telescopes is essential if Australian astronomers are to remain competitive with the rest of the world.* (ANSOC report page 7)

The 20 per cent goal for 8-metre telescope access in the Decadal Plan was pragmatic, not aspirational. It represents a level of investment significantly below that made by other countries, including the nations of the European Southern Observatory (ESO), Canada, the US, and Japan.

One option to rectify Australia's shortage of 8-metre telescope time is the continued support of Magellan and Gemini access by the Australian Government. To retain access at the current levels requires US$4 million per year, which would provide approximately 20 per cent of an 8-metre class telescope.

But Australia's current involvement with both Magellan and Gemini is not straightforward. The Gemini partnership is currently unstable, with the UK withdrawing, and the US Decadal Survey recommending that the US should absorb the Gemini partnership into its own national observatory. The Gemini partnership is planning for a three-year transition period (2013–2015), with new governance arrangements to be negotiated amongst the partners for the period post-2015. In the case of Magellan,

The Universe in numbers

How can we describe the Universe? One of the triumphs of astronomy over the past decade has been to measure the vital statistics of our Universe for the first time through four precise cosmological experiments. Despite our relatively small population, Australian-based astronomers have taken a leading role in three of these fundamental investigations.

Measuring how much stuff there is in the Universe is particularly challenging because most matter in the Universe is dark – dark matter and dark energy. Using the Anglo-Australian Telescope, Professor Matthew Colless FAA of the Australian Astronomical Observatory and collaborators, measured the distances to more than 220,000 galaxies. This cosmological census allowed Matthew's team to precisely measure the amount of matter in the Universe based on the effect of gravity on the distances of the galaxies. In recognition of this work, Matthew and his UK co-leader received the Royal Astronomical Society's first ever Group Achievement Award in 2008.

The Hubble Space Telescope was built with the promise of measuring the current expansion rate of the Universe, a measurement first made by Edwin Hubble, and referred to now as the Hubble Constant. After a decade of work, the Hubble Key Project, co-led by Professor Jeremy Mould FAA of Swinburne University of Technology, measured the Hubble Constant to 10 per cent accuracy. Along with his co-leaders, Jeremy's work was awarded the International Astronomical Union's most prestigious prize, the Gruber Prize in Cosmology in 2009.

However, the Hubble Constant is poorly named because the expansion of the Universe changes over time. In 1998, two teams used distant exploding stars (supernovae) to look back in time; and much to everyone's surprise, they discovered that the Universe's expansion was accelerating. This effect can most easily be explained if the majority of the Universe is made up of some previously unknown dark energy. The work of these two teams was internationally recognised when Professor Brian Schmidt FAA of the Australian National University, along with two other scientists, was awarded the US$1 million 2006 Shaw Prize in Astronomy. Brian also shared the 2007 Gruber Prize with members of both teams, including fellow Australians, Dr Brian Boyle FAA of the Australia Telescope National Facility, CSIRO and Professor Warrick Couch FAA of Swinburne University of Technology.

The results of these experiments, combined with US-led cosmic microwave background measurements, have led to the now standard model of our Universe: it is 13.7 billion years old and composed of 4 per cent atomic matter (such as that which makes up the Earth), 23 per cent dark matter (which has gravity-like atoms), and 73 per cent dark energy (a substance tied to the fabric of space, which causes gravity to be repulsive and which accelerates expansion of the Cosmos).

Jeremy Mould

Australia is not a formal member of the partnership, instead purchasing time on a pay-as-you-go basis. This is a stop-gap arrangement that has little scope for an increase in Australian time or Australian input into future instrumentation, and has the possibility of termination without warning.

The current uncertainty surrounding the Gemini partnership provides a possible opportunity for Australia to increase its share in this partnership, and to reform the governance and instrumentation suite so that they are better aligned to Australian needs. This is an opportunity likely to disappear in the near-term, once the interim and future partnership arrangements are finalised by the Gemini partnership. Increasing our share of Gemini to 13 per cent (equivalent to a 26 per cent share of a single 8-metre telescope), would make a total of 70 nights of 8-metre telescope access available to the community, would cost US$4.3 million per year, and would bring our per capita access in line with the US, Canada, Japan and Europe. Failure to invest in this area will not only mean a loss of current access to 8-metre telescope time, but may make future access nearly impossible – opportunities to join 8-metre telescope partnerships are limited, especially at the level of a full partner with a significant share.

Australia's current portfolio imbalance has come about largely by the way that Australia invests in its infrastructure. Astronomical discovery is powered by large-scale facilities, which are typically funded by either the largest of economies, or (increasingly) by consortia of institutions and/or countries. Effective investment in these facilities requires a long-term strategic approach, ideally providing appropriate access across a wide range of capabilities and hedging the risk and uncertainty of developing new facilities.

Australia has invested heavily in astronomy over the past 50 years, based mainly on opportunities that arose within the political sphere, and often in a way uncoordinated with international partners. This strategy has worked well in the past, delivering internationally competitive infrastructure when it was politically easily achieved. But the scale of the infrastructure is now so large, and facilities so diverse, that Australia's system of doing its own thing is beginning to produce a lumpy portfolio characterised by under and over investment in particular facility types. The inadequate access to 8-metre optical telescopes (and Australia's decision not to join the ALMA mm facility) is symptomatic of the current investment strategy.

Over the next few years, Australia has what is likely to be a limited window of opportunity to join the European Southern Observatory (ESO) – a consortium of 14 European countries and Brazil, which invests in a coordinated set of large-scale optical and radio infrastructure. ESO membership provides a unique opportunity to transition from Australia's current way of doing business to a more sustainable and long-term approach, which should ultimately provide a more efficient allocation of resources for a fixed budget.

ESO is an intergovernmental organisation with some of the world's best telescope facilities. However, it is far more than an assembly of frontline instruments. Fundamentally, it is a process for bringing together countries with a broadly shared vision of needs in relation to astronomy in order to plan, manage and fund a portfolio of telescope facilities. Engagement with ESO requires the Government to develop the machinery to interact with international agencies. Increasing capacity in international infrastructure will have positive effects that reach far beyond astronomy. Astronomy can help lead the way – our scientists are already deeply involved in many overseas committees which set priorities and manage international developments.

Key recommendations

- In the period 2013–2015, Australia must secure access to at least 20 per cent of an 8-metre telescope, in line with the Decadal Plan; 8-metre telescopes are the foundation of a large part of current astronomical discovery. Failure to retain this crucial part of our astronomical portfolio significantly undermines our other astronomical investments.
- Over the next several years, a forward-looking strategic plan for the AAO and the facilities it manages needs to be developed that foresees how the AAO can best serve the community in the future.

- Australia should pursue membership in ESO to gain access to a number of advantages including: a wider spectrum of 8-metre telescopes and instrumentation, ALMA, and secure involvement in the European ELT. At the present time, it is unclear which of the world's three ELTs will reach completion, but involvement in both GMT and the European ELT spreads that risk. Partnership with ESO will also ensure that Australia has the portfolio of infrastructure to support its ambitions for the SKA, both now, and into the future.

Theoretical Astrophysics

Decadal Plan goals

Theoretical astrophysics represents one of three core research capabilities underpinning Australian astrophysical research. As outlined in the Decadal Plan, theory synergies with ground-based optical and radio astronomy maintain Australia's position as a world-leader in the field. Indeed, the demographics report commissioned as part of the Decadal Plan revealed that about one-third of Australian astronomers work in theoretical astrophysics. The Decadal Plan also argues that the historical success of theorists in Australia has often been opportunistic, and acknowledges that:

> *A more strategic approach to planning for theory will be required over the next decade as Australia moves increasingly into very large infrastructure programs.* (Decadal Plan page 23)

Progress against the Decadal Plan

Theoretical astrophysics in Australia has strengthened in the past five years. While the number of astronomers who call themselves theorists (or part-theorists) has remained approximately constant over this time, a recent intake of young, high-impact theorists and numerical astrophysicists into the country has added welcome energy to the theory community. These early- and mid-career researchers bring with them new options for research training at the PhD and postdoctoral levels. These new groups are still small in scale and spread across the country, but are undertaking internationally recognised research and working closely with their observational colleagues to add essential expertise that previously had to be sought overseas.

This new sense of community has been guided (in large part) by the Australian National Institute for Theoretical Astrophysics (ANITA), a chapter of the Astronomical Society of Australia (ASA). ANITA has successfully organised or co-organised at least two theory workshops for the community each year for the last three years. ANITA members also represent the theory community on a number of national level committees.

While theoretical astrophysics is a major research strength for Australian astronomy, it has not benefitted from the funding wedges in the Decadal Plan's proposed research allocation. Its recent growth has occurred, in large part, from serendipitous university-level appointments. Given that *theorists pose many of the questions that drive the next generation of large facilities, and often lead the interpretation of results* (Decadal Plan page 23), it is important that the theory community continue to grow strategically and be well supported.

The period 2011–2015 and beyond

The health of the theoretical community is critical for the overall health of the broader astronomy community. Theory should continue to be nurtured and young theorists should be given opportunities to develop their craft, either for science's sake alone, or as an integral part of current and future observing and instrumentation programs. ANITA should continue to play a leading role in supporting theoretical astrophysics and, where possible, seek to exploit opportunities that will bolster theory in Australia for the benefit of all.

The astronomy community should consider how best to incorporate theoretical astrophysics explicitly within future proposed funding allocations, and how to strategically support theoretical astrophysics at both a national and institutional level. An avenue toward this goal, which has been followed in part within the Super Science Fellowship program, is to support theoretical astrophysics working towards the objectives of large observational programs. While this fulfills the need for strategic support of theoretical astrophysics, it is important for the health and diversity of the community that this support is not limited to those who are part of such large programs.

Key recommendation

- Over the period 2012–2015, under the coordination of ANITA, a strategic plan for theoretical astrophysics should be developed.

High-Performance Computing

Decadal Plan goals

In the area of high-performance computing (HPC), the Decadal Plan recommended that both general (broad use) and dedicated HPC facilities were needed, that computational expertise should cluster around specialised HPC resources, and that connected facilities would be essential, requiring investment in data networks to continue in-step with the increasing volume of data capture. The Decadal Plan also recommended that Australia should continue to participate in the International Virtual Observatory – a facility that aims to collect the archives of the world's major observatories into one distributed database.

Progress against the Decadal Plan

The use of HPC for observational and theoretical astrophysics has increased in Australia over the past five years. Although not resulting from a strategic direction of the Decadal Plan, this has been enabled, in part, by the key Decadal Plan recommendations that there be continued investment in computing infrastructure and associated personnel.

Over the first five years of this decadal cycle, overall investment in HPC infrastructure has been significant. The Australian Government has committed funds to the Pawsey Centre in Western Australia (2009–2013), partly to serve radio astronomy (eg ASKAP, the MWA), but also to act as a general HPC facility for an array of astrophysical purposes. In addition, the Government has supported the National Computational Infrastructure (NCI) facility as a peak computational facility to serve many astronomical HPC users. Finally, gSTAR, a dedicated GPU-based supercomputer funded by the EIF through AAL, will provide a specialised facility for the astronomy community, primarily for theoretical astrophysics, but also for data processing.

One drawback to the increased complexity and volume of astronomy data and simulations – and the need for increasingly powerful HPC to process them – is the necessity of specialists to effectively set-up and exploit the required HPC resources. Such experts are not always astronomers, although many astronomers are required to proxy as experts when the needed personnel cannot be found or funded. In general, the hiring of HPC experts has been positive but unfocused, mainly occurring through opportunistic university funding, or from successful grant applications. While some hiring has occurred at the faculty level, many positions remain on fixed-term contracts. Without continued support, the astronomy community runs the risk of losing this essential expertise when contracts expire.

The period 2011–2015 and beyond

The Decadal Plan of five years ago refers to the coming data tsunami from the next-generation telescopes and supercomputers, but this wave is only now beginning to hit. Of specific importance are the problems involved in efficiently managing this data, including processing, storage, curation and community access. These problems are common to all data-rich sciences, resulting in the emergence of the new umbrella field termed 'eResearch'. eResearch has become a national science priority for the Federal Government, to which they have committed almost $100 million through the NeCTAR (virtual laboratories) and Research Data Storage Infrastructure (RDSI) initiatives. Given the importance of maximising the scientific return from the current and upcoming generation of infrastructure investments, the astronomy community would be well served by investing in data infrastructure at the hardware, software and expert personnel levels. The community will not be able to fully exploit the data taken from current-generation instruments (including ASKAP and SkyMapper) unless the eResearch data challenge is adequately met.

The second issue to be addressed over the remainder of the decadal cycle will be how best to secure adequate operational and personnel funding to support major new HPC infrastructure, such as the Pawsey Centre. Specific focus should be on retaining HPC and eResearch expertise within Australia, and on the best ways in which such experts can work with the astronomy community to enable and sustain international-class science into the future.

Watching supernovae to learn about dark energy

If the stars, planets, galaxies and all that we can see only account for about 4 per cent of the Universe, what is all the rest? The dark side of the Universe – its dark matter and dark energy – is not well understood, and to actually study something that can't be seen requires ingenuity, patience and an understanding of vast astronomical dimensions.

University of Queensland astrophysicist Dr Tamara Davis is using the Australian National University's SkyMapper telescope to track the movement of supernovae. Supernovae are extremely bright and can be used as 'standards' to accurately measure distance and motion across the Universe. By comparing the observed movement of supernovae with their expected movement (based on current cosmological theories), Tamara is hoping to be able to detect and explore the properties of dark matter and dark energy.

In addition, Tamara is part of the WiggleZ Dark Energy Survey. The survey team will measure the distances (redshifts) of 240,000 galaxies and use this information to create the largest-scale map ever made showing the 3D distribution of galaxies in the Universe. Data from the project will help to test new cosmological theories that explain dark energy.

Tamara also uses observations of supernovae in her search for a better understanding of why the expansion of the Universe is accelerating. She was part of the ESSENCE supernovae survey which discovered over 200 supernovae and used these to measure the changing expansion rate of the Universe. She has written a number of papers and articles trying to clear up misconceptions about the Big Bang and the expanding Universe.

In 2009 Tamara was awarded an Australian L'Oreal Women in Science Fellowship. Also in 2009 she received the Astronomical Society of Australia's Louise Webster Prize in recognition of outstanding research by a scientist early in their postdoctoral career.

Tamara Davis

Key recommendation

- Astronomy should build an astronomical data fabric that links high-performance resources through appropriate data middleware and networks to create new opportunities for discovery by Australian researchers based on data flowing from telescopes like SkyMapper, ASKAP and the MWA. A path forward to achieving this goal is for the community to actively engage in the Government's eResearch initiatives, such as NeCTAR and RDSI. AAL has been effective in representing the community's interests, liaising with Government, and seeking out new funding opportunities. The community advocates that AAL continue to represent its interests in the eResearch arena.

Antarctic Astronomy

Decadal Plan goals

The key recommendation within the Decadal Plan regarding Antarctic astronomy was the construction of the Pathfinder for an International Large Optical Telescope (PILOT):

> *A smaller project, but of considerable long-term significance, is the Australian-led PILOT consortium, which aims to operate a pathfinder telescope on the high plateau in the Australian Antarctic Territory (Dome C). There are compelling indications that the Antarctic plateau is the best optical/infrared astronomical site on the planet by a significant margin. Looking further ahead, it may be possible to place a large telescope there that will outperform any other. The PILOT project, while scientifically important in its own right, also points the way to this long-term objective and offers the opportunity for Australia to leverage additional scientific value from its Australian Antarctic Territories.* (Decadal Plan page 33)

Progress against the Decadal Plan

An NCRIS-funded Preliminary Design Study for PILOT was commissioned by AAL in 2007–2008. This study showed that the cost of construction and operation, over a 10-year period, was more expensive than can be contemplated without collaboration with one or more international partners. Based on the outcomes of the study, a proposal was submitted to ANSOC in 2008 to support the Phase B design study of PILOT. While this proposal was unsuccessful, ANSOC noted that *Participation of Australia in Antarctic astronomy is of great strategic value, and the effort of Australian astronomers has enabled Australia to play a role in characterizing the opportunities and challenges for telescopes at areas such as Dome C* (ANSOC report page 15). ANSOC also recommended that greater international collaboration be sought in order to facilitate PILOT or other Antarctic projects of similar scale.

The international landscape

In the last five years there has been considerable international effort aimed at the better characterisation of a variety of Antarctic sites. Much of this has been made possible by the autonomous PLATO site-testing systems designed and built at the University of New South Wales.

China has begun construction of a major station, Kunlun, near Dome A – the highest point of the Antarctic plateau – and is already building the AST3 instrument (an array of three 0.5-metre wide-field optical telescopes) for the site. China is also proposing a more ambitious 4-metre wide-field optical telescope and Australian astronomers have been extensively involved in these developments.

Site testing for a Japanese observatory at Dome F commenced in January 2011, using a PLATO system, in collaboration with the University of New South Wales. A PLATO system is also being funded through EIF and AAL to go to the Ridge A site (200 km from Dome A), in a collaboration between the University of New South Wales, the US National Science Foundation and the University of Arizona. This is aimed at supporting a terahertz (THz) pathfinder telescope. At the South Pole, Australian astronomers are collaborating in a proof-of-concept for a 2-metre optical/UV telescope to map cosmic web emission.

In 2010, the four-year FP6 funded European ARENA network concluded its work and released a final report titled *Vision for European Astronomy and Astrophysics at the Antarctic Station Concordia/Dome C in the Next Decade*. One of the key recommendations listed in the Executive Summary was: *…to start immediately, in 2010, a phase B study for a PLT (Polar Large Telescope) on the basis of the phase A studies made by the Australians for PILOT, for first light before the end of the decade* (ARENA report page 6). European astronomers have submitted an FP7 proposal to fund this phase B study, and this proposal has passed the first selection round. However, it is not yet clear how the Europeans plan to fund the full construction cost of a PLT.

Future opportunities and priorities

The technological explorer facilities now in operation or design at Dome C, Dome F, and Dome A are each intended as the first stage leading towards larger, more ambitious Antarctic telescopes. Over the next five years, it is likely that plans for these larger-scale telescopes will be completed and that work will begin on detailed technical design and science case development.

A 2-metre to 4-metre optical/infrared class telescope (similar to the PILOT concept), imaging in the 2.4 micron niche, still has a strong science justification, based on a wide range of science applications for such an instrument, from asteroseismology to gravitational lensing. However, the feasibility study showed that the lifetime cost of this project would be of the order of $100 million, more than can be considered for funding now.

Antarctic sites (particularly Ridge A and Dome A) could allow us to open a new window, beyond 1 THz, on the Universe from the ground, where several bright diagnostic emission lines from interstellar gas lie. Current access to these windows is from space, eg with the European Space Agency's Herschel satellite. However, while such facilities are far more sensitive than corresponding ground-based facilities, their lifetime is limited and there are significant gaps in their capabilities, for instance in the ability to make large area maps of emission lines. An Antarctic THz facility would be able to undertake such projects and two THz facilities are now under construction: a balloon-borne telescope by the US at McMurdo and the HEAT telescope for Ridge A, a joint US-Australian collaboration supported through EIF funding. Furthermore, China (at Dome A) and Japan (at Dome F), are developing plans for larger-scale (>5-metre class) facilities. A major THz facility has also been proposed for Chile (the Cerro Chajnantor Atacama Telescope or CCAT), for a 5,500 m summit above the ALMA site, reflecting the international interest in this new field.

There are three infrared telescope projects in Antarctica which may develop further over the next five years, led from China, Japan and Europe. The Australian astronomy community should remain open to participation in any of these projects should they progress to the design stage; making use, for instance, of the IP built up through the PILOT concept design study.

Key recommendations

- A project to build a THz observatory, for study of spectral lines in the range of 150 to 400 microns, is a strong candidate for exploratory funding. This is ranked as the highest priority for a new initiative in Antarctic astronomy if increased funding is available in the second half of the decadal review period.
- Continued support for the PLATO program is recommended, and will maintain Australian leadership in this field at a relatively small cost.
- An Antarctic telescope working in the optical and near infrared to study transient astronomical sources is an attractive but potentially expensive option. Possibilities for an international collaboration should continue to be explored, and funding for participation as a partner in such a facility should be considered based on a benefit-cost analysis compared to other facilities.
- A project to build a 2-metre to 4-metre class optical/infrared telescope like PILOT should not be undertaken until an international partner is ready to commit large-scale funds to help with the detailed design and costing work. Thus, PILOT itself is not recommended for further funding as part of the 2006–2015 Decadal Plan.

New and Emerging Research Areas

Ground-Based High-Energy Astrophysics

Ground-based high-energy astrophysics is a research area which has advanced rapidly since the 2006–2015 Decadal Plan was published. The Decadal Plan noted that Australia has an excellent record of achievement in the study of very high energy cosmic rays, and that this research (supported mainly by national competitive grant funding) has a strong international dimension.

The past five years have seen the arrival of several new telescopes capable of detecting photons (of TeV gamma-ray energies) or particles such as cosmic rays and neutrinos (up to ultra-high energies (UHE) above 1018 eV). These high-energy photons and particles are produced in active galaxies, pulsar and neutron star environments, jets and accretion associated with black holes and neutron stars, supernovae and their remnants, and possibly in the formation of the most massive stars.

The production and propagation physics of gamma rays, cosmic rays and neutrinos ties them intimately to astronomy at lower energies – from radio to X-rays – thus linking ground-based high-energy astrophysics with Australia's core programs in radio and optical astronomy. It also links this research area to several of the key science questions identified in the Decadal Plan. Australian astronomers (observational and theoretical) are increasingly using information from this rapidly-emerging field.

Australia has an active and influential role in ground-based high-energy astrophysics activities, and is a member of two major international collaborations – the High Energy Stereoscopic System (H.E.S.S.) for TeV gamma-ray astronomy, and the Pierre Auger Observatory for UHE cosmic-ray astronomy. Australia's subscription to the Auger Observatory is currently sourced from ARC funds. Annual Auger and H.E.S.S. subscriptions should be considered for funding under any successor to NCRIS. This stream of funding would provide highly desired stability and could be extended to include Australian involvement in other high-energy observatories.

Australia is also using its radio expertise to undertake innovative experiments in high-energy neutrino astronomy. Because neutrinos travel in straight lines from their sources, undeflected by magnetic fields and unimpeded by matter or background radiation, they provide a unique way of studying high-energy processes in the Universe. The Australian-led Lunar UHE Neutrino Astrophysics with the Square Kilometre Array (LUNASKA) project is designed to detect UHE neutrinos using the lunar Cherenkov technique. In this project, ground-based radio telescopes are combined with specialised signal-processing hardware to focus on the Moon and utilise it as a gigantic neutrino telescope.

Key recommendations for Ground-Based High-Energy Astrophysics

- Australian participation in H.E.S.S./H.E.S.S.-II and future ground-based gamma-ray telescope projects should be continued. The next few years should see clear timelines for the developments of the next generation of instruments and their location. Funding should be at a level to enable a consortium of several Australian institutes to contribute personnel, modest hardware support and subscription fees in order to guarantee a share of observation time and influence in the scientific agenda.
- Participation in the southern Auger Observatory should continue, and the capacity to participate in Auger North should be expanded via a contribution of $200,000 to Auger North hardware over the next five years.
- Funding of LUNASKA should be continued, with the project extended to use the advanced detection technology developed for ASKAP (modified for lunar Cherenkov observations).

Clues from ultra-high energy collisions

If you were going to study the highest energy particles in nature where would you look? At the Moon, of course! However, looking to the lunar surface for help in understanding the physical fundamentals of the Universe might not be an intuitive first choice – unless you are a high-energy astrophysicist like Dr Clancy James.

Ultra-high energy (UHE) cosmic rays – subatomic particles that seem to have extreme kinetic energy – have been studied for over half a century but their origin and much about them remains unknown. Clancy and his colleagues at the University of Adelaide are working to resolve this mystery through applying the lunar Cherenkov technique. This technique uses radio telescopes focused on the Moon to search for short-duration pulses of Cherenkov radiation emitted as a cascade when an ultra-high energy particle collides and interacts with the Moon's surface. By analysing the observed radiation Clancy can identify the particle that initiated the cascade.

Clancy's work is part of the LUNASKA project, which is an ongoing project aimed at developing techniques for detecting high-energy particles with the next generation of radio telescopes.

In 2010, Clancy was awarded the Bragg Gold Medal by the Australian Institute of Physics for the best PhD thesis by a student from an Australian university. Also in 2010, Clancy received a Netherlands Organisation for Scientific Research Rubicon award and is currently in Nijmegen, The Netherlands, continuing his work on cosmic rays using LOFAR, one of the world's largest radio telescopes.

Gravitational Wave Astronomy

Gravitational waves have not yet been directly detected, but gravitational-wave astronomy and astrophysics have recently become very active areas of research. In the five years since the publication of the 2006–2015 Decadal Plan, Australian physicists have continued to prepare for the international Advanced LIGO (Laser Interferometer Gravitational Wave Observatory) facility, and ACIGA has recently raised the possibility of hosting a third Advanced LIGO detector in Western Australia. Over the same period, a new approach to the detection of gravitational waves using pulsar timing has advanced rapidly, building on Australia's strengths in pulsar astronomy.

The international Advanced LIGO project now under construction will provide a ten-fold improvement in amplitude sensitivity and bandwidth over current facilities, corresponding to an expected detection rate of almost one neutron star coalescence event per week. Recent results suggest a similar number of detectable black hole coalescences. Thus gravitational wave detection appears to be highly likely once these advanced detectors are operational.

For astronomers, it is essential to be able to identify the source responsible for gravitational wave emission, determine its characteristics, and place it among the classes of known objects. A global network of detectors with an Australian node offers a significant improvement in measuring the sky location of gravitational wave sources. Depending on the signal-to-noise ratio and the location

Clancy James

on the sky, the ratio of the uncertainties in the position of a source can be 5- to 10-times smaller with an Australian node than without. In many places on the sky, assuming reasonable signal-to-noise, the uncertainty in position approaches one degree, which may be sufficiently small to enable electromagnetic astronomical identification of the source. Australia's wide-field suite of instrumentation using the AAT, SkyMapper, ASKAP and the MWA are ideal for this purpose.

Key recommendation for Gravitational Wave Astronomy

- We anticipate considerable interest in gravitational wave astronomy once sources are finally detected. Until this time, ground-based gravitational wave instrumentation primarily resides in the realm of experimental physics. It is unlikely that gravitational waves will be detected by ground-based detectors before 2015, and therefore Australian astronomy's priorities remain primarily focused on supporting our optical and radio portfolios, which continue to be the workhorse facilities for research on all types of cosmic phenomena, including future discoveries made by ground-based gravitational wave detectors like Advanced LIGO.

Pulsar timing and detection of gravitational waves

Direct detection of the gravitational waves predicted by Einstein's general theory of relativity remains one of the great goals of modern astrophysics. Although pulsar timing of double-neutron-star binary systems has given strong evidence that gravitational waves exist at the predicted level, up to now there has been no direct detection. Over the past few years it has become clear that precise timing of an array of millisecond pulsars has the potential to directly detect gravitational waves in our Galaxy. Millisecond pulsars are such extraordinarily precise clocks that even the tiny perturbations of spacetime expected from celestial gravitational wave sources are potentially detectable as correlated fluctuations in the observed pulse periods of different pulsars. Pulsar timing arrays (PTAs) are sensitive to gravitational waves with frequencies in the nanoHertz band and are therefore complementary to existing and proposed laser-interferometer gravitational wave detection systems.

The Parkes Pulsar Timing Array (PPTA) began regular observations in 2005, using the Parkes 64-metre radio telescope to observe a set of twenty millisecond pulsars at three frequencies, typically at two-week intervals. The project is a collaboration primarily between groups at CSIRO Astronomy and Space Science and Swinburne University of Technology, with significant contributions from other individuals or groups in Australia, the US and China. New instrumentation has been developed for real-time processing of the pulsar data, resulting in high-quality pulse profiles and accurate pulse arrival times, vital for achieving the scientific goals. The PPTA group has also developed advanced off-line signal-processing systems for data analysis as well as simulation of likely signals to aid in interpretation of the results obtained.

These efforts have produced a world-leading data set that is approaching the level needed for a successful detection of astrophysical gravitational waves. For PTAs, the most likely detectable signal is a stochastic background of gravitational waves from coalescing super-massive black holes in the cores of distant galaxies. Limits on this background from existing data have already begun to constrain some models for the co-evolution of galaxies and their central black holes. Fortunately, the sensitivity of PTAs for gravitational wave detection is a strong function of data span and so, with continued observations, prospects for a successful detection in the next few years are good. This will also be helped by efforts already under way to combine the PPTA data set with those from European and North American PTA projects to form an International Pulsar Timing Array.

Teachers' workshop on the 'Dish', CSIRO Parkes Radio Telescope

Education and Public Outreach

The Australian astronomy community is committed to educating the public about our Universe, and also about how science is conducted and how knowledge is gained. The past five years have seen some noteworthy achievements and positive developments in bringing astronomy to students and the wider public.

The 2006–2015 Decadal Plan noted the declining number of science teachers, including teachers trained in astronomy. The forthcoming National Science Curriculum for years K–10 and senior classes includes a significant amount of astronomy and space science, so there is potential for the Australian astronomy community to be involved in providing professional education for teachers in this area.

The Decadal Plan mentions the need for more effort and funding to go to disseminating research results. While it is true that the media and the general public are interested primarily in results (with less emphasis given to processes), in the education arena process is more important than 'findings', and it may be becoming more important in other, public, contexts, too. To explain what science is, and what it is not, how scientists work should be highlighted as much as what they find.

Inspiring Australia: a national strategy for engaging with the sciences was launched in February 2010 by Senator the Hon Kim Carr, Minister for Innovation, Industry, Science and Research. It sets out a strategy for public engagement with science and thus provides the context within which Australian science communication efforts should now be considered. The report overview notes that:

> *Significant investment is being made in many areas including astronomy, space science, marine science, climate change, nanotechnology and advanced ICT [information and communication technology]. Now is the time to showcase this to Australians and the world.* (*Inspiring Australia* page xiii)

Astrofest in Perth 2011

The *Inspiring Australia* report makes 15 recommendations. Most will have some implications for astronomy outreach, but two are particularly pertinent:

> *Recommendation 11*
>
> *That a key focus of the national initiative should be raising awareness among young people of opportunities in science and research. The Australian Government's investment in schools, higher education and research should be harnessed to achieve this.* (*Inspiring Australia* page xix)

and

> *Recommendation 12*
>
> *That the national initiative support science communication exhibitions and programs that target under-served groups, such as those living in outer metropolitan, regional and remote areas; Indigenous communities; people for whom English is a second language; and people who are disabled or have limited mobility.* (*Inspiring Australia* page xx)

Successful educational and public engagement involves both telling audiences what we want them to know *and* thinking about what our audiences want to know and the mode in which they want it delivered, and then responding appropriately.

The International Year of Astronomy

The UN International Year of Astronomy (IYA) was celebrated in 2009. It commemorated the 400th anniversary of the first use of an astronomical telescope by Galileo. Internationally, IYA was a huge success, with more than 815 million people across 148 countries taking part. In Australia there were over 500 IYA events.

One of the key reasons for IYA's success was that astronomy has so many facets – science, technology, history, biography, symbolism, architecture – that it provides many entry points. Astronomy can be connected with a huge range of other interests and activities.

In Australia there was a plethora of successful grassroots events, organised and delivered by people close to the communities they were aimed at: art and photography exhibitions, talks, concerts, viewing nights and more.

One activity funded under the IYA program has been a book of 'stories' – short pieces of text, about 200 words in length – mostly on individual research projects carried out by Australian astronomers. The printed book was completed in 2011, with the stories also placed online. When taken as a body, the stories give an overview of Australian astronomy and if this first example is seen to provide value for money, the Australian astronomy community may wish to repeat the exercise regularly.

For instance, Professor Fred Watson AM, of the Australian Astronomical Observatory, is an extremely successful science communicator because he is willing to speak on essentially any astronomical topic, to use an interactive medium (radio) and to make a regular, repeated effort, which has established him as a credible source. In the period of this review, Fred has been honoured with the Australian Government Eureka Prize for Promoting Understanding of Science, 2006; Queensland Premier's Literary Award for Science Writing, 2008 (for *Why is Uranus upside down?*); APRA Award for Best Choral or Vocal Work, 2008 (for 'Star Chant'); and Member in the General Division of the Order of Australia (AM), 2010.

It could be argued that the education and public outreach goals for the first half of the 2006–2015 Decadal Plan were exceeded by a large margin in this period due to the International Year of Astronomy (IYA). The events of this single year were more than would be reasonably expected to occur within a decade. A vast amount of educational and public outreach material was generated by IYA which will continue to be used in subsequent years. However, if funding were made available for improving access to this material by schools and the public (eg a one-stop website) the value could be increased.

Funding for grassroots activities is highly valued. In 2009 the Astronomical Society of Australia (ASA) allocated $8,000 for awards to community groups for IYA activities. There was huge interest in this, with over 50 applications received. While running such a scheme has costs, both financial and in terms of the time to assess proposals and then evaluate the programs run, it provides a direct link between the astronomers (as represented by the ASA) and the wider community. April 2011 was Global Astronomy Month, one of the legacies of IYA. If Global Astronomy Month becomes established as a regular event, funding could be designated specifically for events being held then.

The Re-Trial of Galileo, UNSW

Seven sisters, an emu and a jewel box – Australian indigenous art and astronomy

Imagine being deep in the bush on a moonless night. Listen for the quiet shuffling of nocturnal animals. Look above for brilliant ilgarijiri – 'things belonging to the sky' in the Wajarri Yamatji language from Western Australia. The sight is primordial and breathtaking.

Ilgarijiri is also the name of a joint project between staff and artists of Yamaji Art in Geraldton and Professor Steven Tingay from the International Centre for Radio Astronomy Research at Curtin University. As part of the 2009 International Year of Astronomy celebrations, the exhibition brings together astronomers and Aboriginal artists – a collaboration between the world's oldest continuing cultural understanding of the sky and state-of-the-art astronomical technology.

For inspiration, artists and astronomers travelled to Mullewa and Boolardy Station – land on which the scientists hope the international Square Kilometre Array radio telescope will be built – and around a campfire, discussed different perspectives on astronomical objects and constellations. The site has great significance to both ancient and modern times: it is an area rich in indigenous culture and is also one of the most interference-free places on Earth, which is crucial for the highly sensitive radio telescopes.

The exhibition features the work of 30 Indigenous artists and has been seen by several thousand people in showings at the Geraldton Regional Art Gallery, Curtin University's Resources and Chemistry Precinct and the Australian Institute of Aboriginal and Torres Strait Islander Studies in Canberra. The exhibition also travelled to Cape Town, South Africa, as part of the Communicating Astronomy to the Public 2010 conference.

See the exhibition's story and artworks at www.astronomy.curtin.edu.au/ilgarijiri/index.html

The Seven Sisters (Christine Collard)

Galactic All-Sky Survey

Priorities and Implementation Plans

The Australian astronomy community remains committed to the goals of the 2006–2015 Decadal Plan. Astronomy has been well funded over the past five years, so future funding requests will need to be carefully planned and justified. Over the next five years, we aim to build on Australia's current high standing in world astronomy, and to ensure that the new research facilities funded during 2006–2011 are scientifically productive at the highest international level.

Strategic landscape

The broader strategic landscape needs to be taken into account in setting our priorities and plans for the future. Astronomy, together with the wider research and innovation area, has benefited from the injection of stimulus funding as part of the Government's response to the global financial crisis of 2007–2008. This made it possible to bring forward some of the expenditure on new capital facilities (especially those related to the SKA and ELTs) which had originally been planned for 2012–2015 and beyond.

At the same time, we are currently in transition between the NCRIS scheme for funding major research infrastructure and operational costs (which ends in 2011) and its replacement by a new research infrastructure funding scheme whose details are yet to be announced. This has led to uncertainty about the continuity of operational funding for existing facilities, as well as a lack of operational funding for some of the new facilities for which construction funding has now been allocated.

Many of the strategic issues currently faced by Australian astronomy are also relevant to other areas of the wider research and innovation sector. They include:

i the need for stable, long-term operational funding for major national and international research facilities

ii the desirability of a clearer process for funding the construction of landmark research facilities, and the need to develop clear processes for engaging with overseas research organisations for access to international-scale infrastructure

iii the low level of basic research grant funding available through the ARC

iv the need to build on the Super Science initiative and provide longer-term career paths for young scientists.

Anglo-Australian Telescope

Some of these issues are acknowledged in the Government's recent *Strategic Framework for Research Infrastructure Investment* discussion paper, and we are strongly supportive of the principles outlined in this paper.

Priorities for 2011–2015

The priorities of the Australian astronomy community for the second half of the Decadal Plan period are (in priority order):

1. Ensuring that Australia is in the best possible position to participate in and host the international SKA. This includes continued development and operations of ASKAP, protection of the radio-quiet zone in Murchison, Western Australia, and rationalised operation of the existing national facilities for radio astronomy.
2. Securing long-term access to forefront optical facilities via membership in ESO or a revitalised partnership with Gemini and/or Magellan, including access to 8-metre class telescopes at the minimum level of 20 per cent set out in the Decadal Plan. This is an issue of particular urgency.
3. Continuing support of the Australian Astronomical Observatory and the AAT at current levels up to 2015, including the delivery of the NCRIS-funded HERMES instrument and the continued development of innovative instrumentation concepts for deployment at the AAT and on other international facilities.
4. Continuing Australia's involvement in the Giant Magellan Telescope (GMT), including engagement with other partners so that full GMT construction funding is secured. Continued development of links with industry to ensure that Australia's investment in the GMT produces economic as well as scientific returns.
5. Investment at a national level in eResearch-related hardware and software systems and the expertise to set-up and manage them. This capacity, shared across the science and technology sector, is needed if we are to fully exploit the coming data tsunami from the current and upcoming telescopes and instruments.

The community also places a high value on supporting the breadth of astronomical discovery through small- to medium-scale investment in the areas of theoretical astrophysics, Antarctic astronomy and ground-based high-energy astrophysics, as well as through university-based research facilities.

Computational astrophysics and high-performance computing are growing rapidly in importance. As we move into the next decadal plan cycle (2016–2025) our community will need to transition from the current peta-scale HPC to exa-scale HPC. As we plan for this transition, astronomy should engage with other sciences, industry, and international partners to offset the formidable costs and uncertainties. It is inevitable that this transition will be required in order to accommodate future projects such as the SKA.

Implementation plans

The current NCRIS funding scheme ends in 2011 and our implementation plan for 2011–2015 needs to take into account current uncertainties in the timing and scope of future funding rounds. The following implementation plan is based on the landscape at the start of 2011:

- In the period 2013–2015, Australia must, at a bare minimum, secure access to 8-metre telescopes at the Decadal Plan rate of 20 per cent of an 8-metre telescope. There are two possible routes to securing 8-metre access: Gemini/Magellan or ESO membership. The astronomy community's clear preference is ESO membership, but we recognise that funding for this is unlikely to be available before 2015 and so both options should be pursued in the short term.

- The AAL/National Committee for Astronomy ESO Working Group will continue to develop a business case in 2011, and AAL will continue discussions with Government about the feasibility and timing of Australian membership in ESO in the 2015 time frame.
- The period 2011–2015 will see the new ASKAP and MWA radio telescopes in Western Australia come into full scientific operation, supported by the data processing and analysis facilities of the Pawsey Centre. To maximise the scientific return from Australia's large capital investment in these facilities, it is essential that they have adequate operational funding over the period 2013–2018.
- Long-term protection of the radio quiet zone in Western Australia is vitally important for the future of radio astronomy, both in Australia and worldwide. CSIRO will need to continue an active engagement with the Federal and Western Australia Governments to secure and maintain this protection.
- Australia should engage strongly with European and US radio-astronomy communities over the next five years, as preparations for the first phase of the Square Kilometre Array (SKA1) intensify. This engagement should embrace new initiatives such as the proposed US HERA, as well as the growing scientific and technical collaborations built around ASKAP and the MWA. This engagement should capitalise on CSIRO's expertise in the relevant engineering and technical areas.

Following the large capital investment in Australian astronomy during the past five years, a key challenge for 2011–2015 is finding sufficient operational funding for these new facilities. The solution will involve trading off expenditure across the astronomy portfolio and the community and stakeholders will need to prioritise spending on new facilities relative to existing ones. Even when this is done as efficiently as possible, the size and remote location of the new radio facilities (together with the end of the NCRIS program which provides the majority of operational funding for optical 8-metre telescopes) mean that some new funding will be needed for operations in 2013–2015 and beyond.

In its plans to pay for the full cost of research through the ARC, the Government has made significant progress towards the Decadal Plan's request to provide an avenue by which long-term running costs of university research infrastructure are supported. Because some university astronomical infrastructure is shared, a mechanism by which external users could contribute to the operational costs of university-level facilities through, for example, the grants program, would be a useful addition to the current program.

Governance and planning

CSIRO has led Australia's involvement in the SKA, and will operate ASKAP together with the existing national facilities for radio astronomy. CSIRO should continue leadership in this area, while also ensuring that it consults with the broader astronomy community when making major decisions, and that investments in astronomy are consistent with the Decadal Plan.

The AAO is resourced both to operate the AAT as an internationally competitive research facility, and to serve as a national observatory which can deal with the operational aspects of Australia's access to international optical facilities (such as time allocation and scientific and technical user support). The AAO should continue in both these roles, making sure that the astronomy community is consulted when making major decisions and that investments are consistent with the Decadal Plan.

AAL was set up in 2007 to manage NCRIS investment, which supports both new infrastructure and the operations of existing facilities. It has proved to be successful in managing strategic and funding issues for a broad range of national and international facilities, including the management of Australia's subscription to international facilities like Gemini and Magellan, where it has been able to handle exchange-rate risks very effectively. AAL should continue to negotiate Australian access to 8-metre telescope time and represent the Australian community on the GMT Board. AAL should also take a leading role in liaising with Government to help secure Australia's participation in ESO. AAL's ability to continue in this role depends on there being a funding program, such as a successor to NCRIS, which it can manage.

The NCRIS scheme was a highly successful model for funding research infrastructure and operational costs, which we would like to see continued in the future. Over the past four years, AAL has shown that it is able to respond rapidly to new funding opportunities and prioritise investment across the broad astronomy portfolio. If funding becomes available from a new NCRIS-like scheme, we recommend that AAL should broker and manage investments in all areas which do not directly overlap with the roles of the national observatories.

In the 2011–2012 time frame, both CSIRO and the AAO will be carrying out a review and priority-setting exercise, in consultation with users, to assess how current revenue streams for operational funding can be directed most effectively in the longer term. AAL should then prepare an updated Astronomy Roadmap in 2012–2013 which takes into account the rapidly-changing international landscape with respect to Gemini, the SKA and ESO, as well as other developments nationally and internationally.

It would also be valuable for AAL to have a role in coordinating and commenting on all proposals which request new federal funding for astronomy, to ensure that these have broad community support and are consistent with the aspirations of the Decadal Plan.

The National Committee for Astronomy (NCA) oversees the Decadal Planning process under the auspices of the Australian Academy of Science. The NCA should continue in this role, and begin preparations for the 2016–2025 Decadal Plan by 2015.

Funding profile 2006–2015

Capital expenditure

The first five years of the Decadal Plan period have seen a major investment in new astronomy infrastructure and facilities, with a total capital expenditure of $230 million (in 2005 dollars)[4] over the decade 2006–2015. This includes $130 million for radio astronomy facilities and support (mainly for ASKAP, but also including the MWA and a 25 per cent share of the Pawsey Centre), and $100 million for optical astronomy (mainly for the GMT, but also including some additional funding for the AAO).

The Decadal Plan set an overall goal of $125 million for new capital investment in national and international research facilities over the decade 2006–2015, so the actual capital expenditure has been almost double what was anticipated. There are two main reasons for this: ASKAP is now a larger and more powerful facility than envisaged in the Decadal Plan, and major capital expenditure in the GMT has been made earlier than originally envisaged as the result of a successful university-led proposal to the EIF scheme.

Figure 1 shows the current astronomy funding profile (committed and expected funds) for the period 2006–2015.

The overall funding balance is different from what was envisaged in the Decadal Plan, leading to some serious funding gaps and future uncertainties. While the goal for investment in the SKA from 2006–2015 has been met and exceeded by the ASKAP program, and the target for investment in an ELT has been met on a faster time scale than envisaged, there is currently no funding to maintain any access to 8-metre class optical telescopes after 2015, with access to 8-metre access in the 2013–2015 time period approximately half of the 20 per cent decadal plan goal. Investment in new instrumentation for 8-metre class telescopes has also been lower than expected, due to the cancellation of Gemini's Aspen instrument upgrade program.

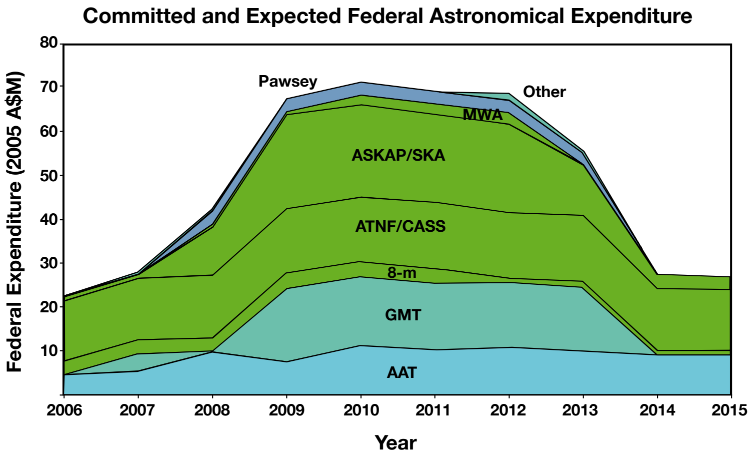


Figure 1: Committed and expected funding (from Federal Government sources) for Australian astronomy from 2006–2015, in 2005 A$. This includes both capital and operational expenditure for national and international research facilities, but excludes national competitive grant funding provided by the ARC.

Operational expenditure

Figure 2 shows the overall astronomy budget for 2006–2018 (extending three years beyond the 2006–2015 time frame of the current Decadal Plan), split between capital and operating expenditure. The Decadal Plan estimated an operational expenditure of $22 million per year (in 2005 dollars) for Australian astronomy facilities in 2006, rising to ~$26 million per year in 2015.

The current operating budget for Australia's major astronomy facilities has recently been increased through augmentation of the AAO's operational budget after UK withdrawal, as well as a small augmentation of CSIRO's astronomy budget to support ASKAP, and the total operational expenditure in 2010 was close to $25 million (2005 dollars) per year.

It is generally agreed that the annual operating costs for a major astronomy facility are typically 10 per cent of the capital cost of building the facility. As the 2008 ANSOC report noted:

> *There is debate in the community about what fraction of the capital costs are needed per year to support the long-term viability of a national/international facility at the forefront of astronomical capability, but once all the above aspects of the operational phase are taken into account, the typical figure is about 10%. …The current emphasis on lifecycle costs in the USA has brought this issue to the attention of the science community, and it has become routine at NASA, NSF and DOE to make a "bottom-up" assessment of the likely lifecycle costs as part of the evaluation and review process before approval of development funding.* (ANSOC report page 13)

The community's goal for the period 2011–2015 is to reach and sustain a stable operational budget of $36 million per year (in 2005 dollars) for our major astronomy facilities. This is $10 million per year higher than the $26 million per year level set out in the Decadal Plan, mainly because of the need to operate new facilities with a capital value $100 million higher than anticipated in 2005. This level of $36 million per year for operational funding includes ESO subscription fees, and thereby substantial provision for future capital upgrades to the entire astronomical portfolio. With appropriate internal reallocations over time, this amount should support Australia's full portfolio of astronomy investments into the foreseeable future, ie to 2020 and beyond.

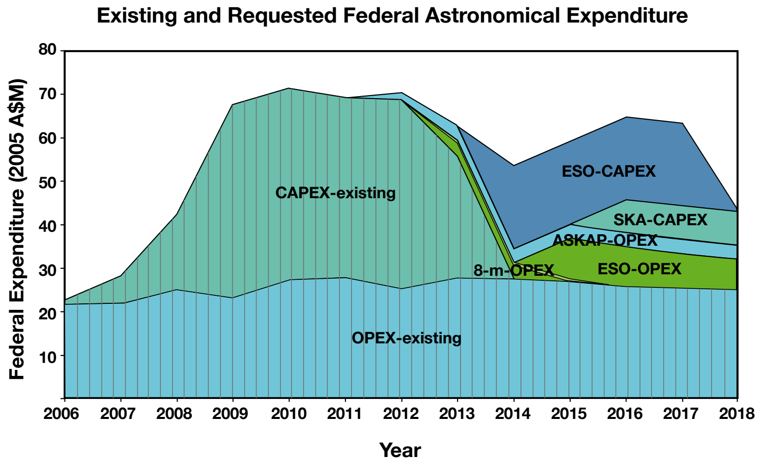


Figure 2: Federal Government expenditure on astronomy, as in Figure 1 but now divided into capital (CAPEX) and operating (OPEX) expenditure and extended forward in time to 2018.

Funding profile 2011–2015

The astronomy community's funding requests for the next five years are intended to make the transition to steady-state operational funding at the level of $36 million per year (in 2005 dollars) for Australia's national and international astronomy facilities. No further capital expenditure for astronomy is requested before 2014.

To *operate* the new facilities funded over the past five years, and provide 8-metre access at the 20 per cent level, will require an additional investment of $10 million per year (in 2010 dollars). This is made up of $6 million per year to replace the operational funding currently provided by NCRIS (mainly for 8-metre access, but including $1 million per year to support small- to medium-scale facilities like the MWA, the Pierre Auger Observatory and the Antarctic pathfinder experiments), together with $4 million per year in additional operational funding for CSIRO to meet the full running costs of ASKAP.

Funding beyond 2015

In the 2015 time frame (ie close to the start of the 2016–2025 Astronomy Decadal Plan), we foresee the need for new capital investment to support Australia's participation in SKA1 and ESO membership (or an increased share of a revitalised Gemini/Magellan).

This capital expenditure will also require supporting operational expenditure, much of which can be redirected from existing lines of funding (see Figure 2). The two options for Australian optical astronomy from 2015 are:

- *ESO membership*: In addition to a joining fee, the cost of ESO membership would be about €10 million per year. This would provide a 28 per cent share in an 8-metre telescope, but would also give Australia a 7 per cent share of the European ELT, as well as access to ALMA, the wide-field VISTA and VST optical/IR survey telescopes and the VLT interferometer. While the cost of ESO membership is higher than for Gemini/Magellan, it also provides a much broader suite of telescopes and instrumentation and provisioning for future instrumentation and telescopes, such as the European ELT. Australia would remain a major partner in GMT, thereby achieving the Decadal Plan goal of 10 per cent of an ELT.
- *Gemini/Magellan*: The current cost to obtain a 20 per cent share of an 8-metre telescope through Gemini and/or Magellan, is US$3.4 million per year. Since participation in Gemini/Magellan does not provide the running costs associated with an ELT, additional operational costs would need to be found for the GMT in the future (estimated to be US$2 million per year for Australia's 5 per cent share), although the GMT Founders Agreement does allow partners to trade off between capital and operational expenditure.

National competitive grant funding

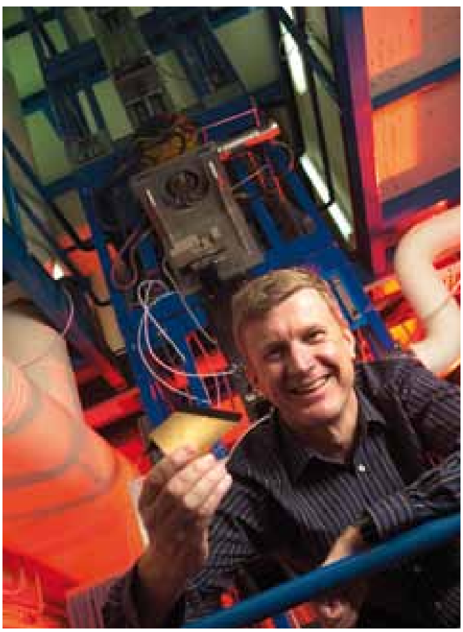
The Decadal Plan noted that an increase in ARC research support for university-based astronomers was essential to leverage the maximum scientific return from new research facilities.

The ARC funding awarded for Discovery Projects in astronomy has not increased since 2002, but the Decadal Plan goal of an increase of $3 million per year in competitive grant funding has largely been met through the award of new funding from Super Science and Future Fellowships, together with the new ARC Centre of Excellence in All-Sky Astrophysics (CAASTRO). This new funding for astronomy is extremely welcome, but the low level of overall funding for the national competitive grants program, and in particular for the more flexible ARC Discovery Projects scheme, remains a broader strategic problem for Australian science.

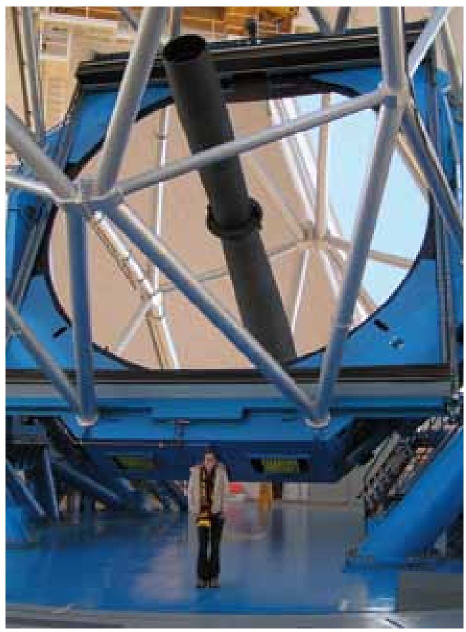
Appendix C updates some of the demographic data in the 2006–2015 Decadal Plan and shows that the Australian astronomy community has grown in size by at least 20 per cent over the past five years – as envisaged in the 2005 Decadal Plan.

Much of this growth has come through an increase in the number of PhD students and early-career researchers funded through the ARC's national competitive grants programs. It will be important to harness the skills of these young researchers in the longer term by ensuring that funding streams are directed in a balanced way, so that there is also support for mid-career and longer-term positions. For example, if the Super Science Fellowship program is continued in the future, it would be valuable to make some of these fellowships available to more experienced researchers as well as recent PhD graduates.

We also encourage universities and host institutions to develop strategic plans for fostering the career path of their ARC-funded fellows – this is particularly important after the completion of a fellowship.



Astrophotonics research



Gemini South telescope

Magnetism, music and the Cosmos

When we look into the sky and see the same constellations that prehistoric people saw it is easy to believe that the stars and planets are unchanging and unchangeable – but we'd be wrong about that! According to Bryan Gaensler, Professor of Physics at the University of Sydney, the Universe is a bubbling, seething dynamic place where stars are born, live and die.

As a graduate student working with CSIRO's Australia Telescope, Bryan discovered that the remnants of many exploded supernovae in our galaxy line up with the Milky Way's magnetic field like 'cosmic compasses'. His research continues to shed light on astrophysical magnetism. Through his development of innovative spectropolarimetric techniques he has derived detailed 3D maps of the large-scale magnetic fields in the Milky Way, the Magellanic Clouds and in distant galaxies.

In 2009 as part of the International Year of Astronomy celebrations, the University of Sydney School of Physics and the Sydney Conservatorium of Music Brass Ensemble combined to present Music and the Cosmos. Professor Tim Bedding, Professor Geraint Lewis and Bryan each delighted the audience with entertaining and accessible explanations of the latest explorations in astronomy. Among a number of insights, Bryan explained how supernovae generate energetic subatomic bullets known as cosmic rays, and leave behind incredibly magnetic, dense, collapsed stellar remnants known as magnetars.

Bryan is an Australian Laureate Fellow and world-renowned astronomer. He has been a Hubble Fellow at the Massachusetts Institute of Technology, a Clay Fellow at the Smithsonian Institution and an Associate Professor at Harvard University. In 2006 he received the Newton Lacy Pierce Prize in Astronomy from the American Astronomical Society. Bryan was awarded an ARC Federation Fellowship in 2005, and received the 2011 Pawsey Medal from the Australian Academy of Science. He is currently Director of the ARC Centre of Excellence in All-Sky Astrophysics (CAASTRO).

Bryan Gaensler

Siding Spring Observatory

Appendix A: The Mid-Term Review Process

The decision to undertake a Mid-Term Review of the 2006–2015 Australian Astronomy Decadal Plan was made at a meeting of the National Committee for Astronomy (NCA) at the Australian Academy of Science in December 2009. The National Committee also set down Terms of Reference for the review, and appointed a seven-person committee to carry it out.

The members of the NCA Mid-Term Review Committee were Elaine Sadler (Chair), Kate Brooks, Scott Croom, Darren Croton, Brian Schmidt, Lister Staveley-Smith and Stuart Wyithe.

Terms of Reference

The Mid-Term Review of the Decadal Plan for Astronomy 2006–2015 will:

1. *Re-affirm the main goals and priorities of the Decadal Plan, and provide a succinct update on the state of Australian astronomy and significant changes since the completion of the Decadal Plan*
2. *Review the recommendations of the Decadal Plan, reporting on the extent to which they have been accomplished and whether unfulfilled recommendations remain appropriate or require revision*
3. *Review current plans for implementing the original or updated recommendations of the Decadal Plan, and provide revised implementation plans with the priorities and contingencies, focusing on the period 2011–2015 but addressing the longer term where appropriate.*

Timeline for the Mid-Term Review

The Mid-Term Review (MTR) Committee met regularly, in person or by teleconference, between March and November 2010. To solicit input from the wider astronomy community, the MTR committee prepared an Issues Paper, circulated in June 2010, which summarised the key goals and recommendations of the 2006–2015 Decadal Plan, and the progress made to date on achieving these goals. The Issues Paper was also presented and discussed in an open session at the July 2010 ASA meeting in Hobart, and submissions in response to the issues raised were received from a range of groups (including the key advisory committees listed below) as well as from individuals.

The MTR committee then prepared a draft report and list of recommendations, which were presented and discussed at a series of 'Town Hall' meetings in Sydney, Melbourne, Canberra and Perth in

Stefan Keller and SkyMapper

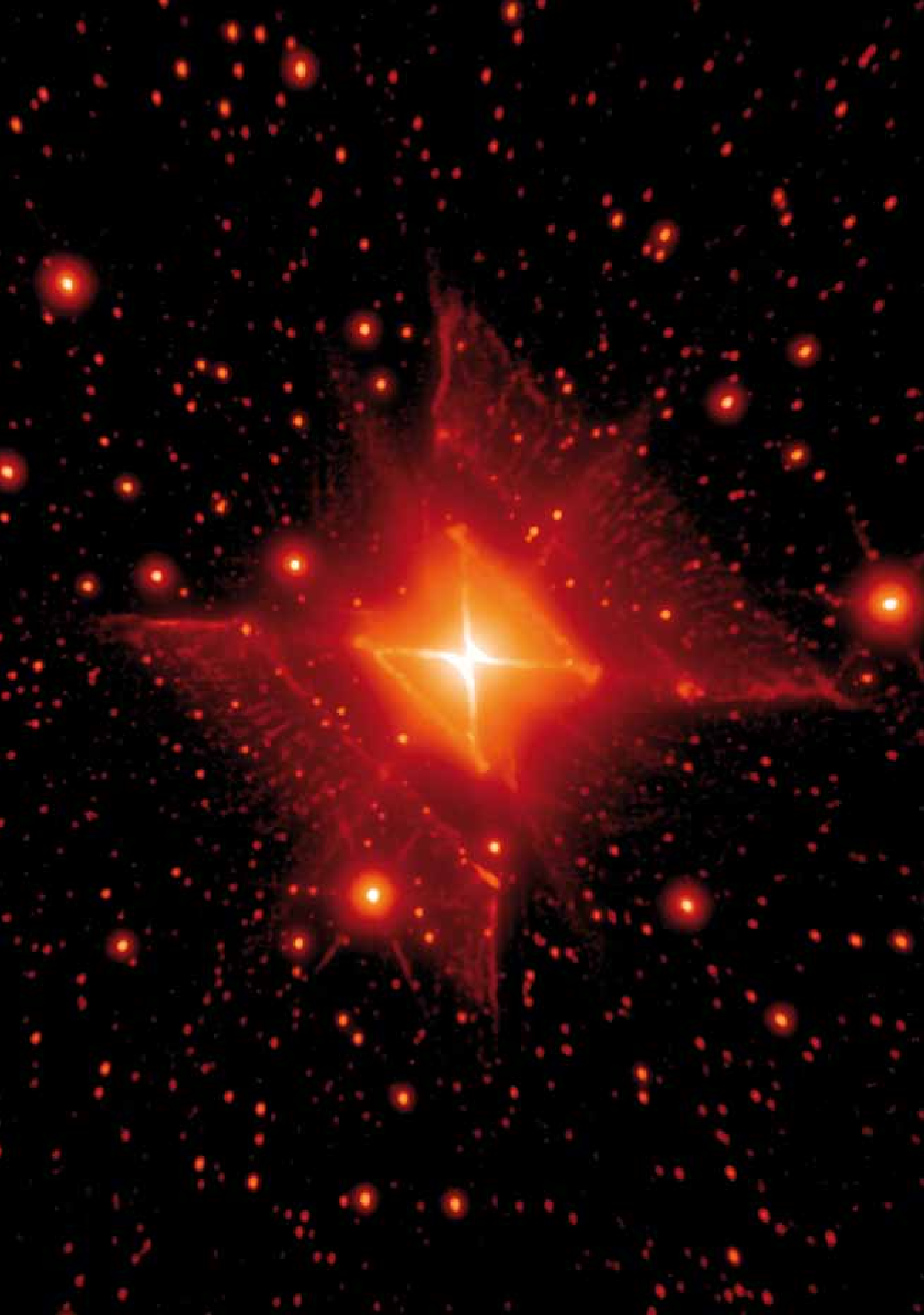
November 2010. Based on these meetings, and discussions at the NCA meeting in December 2010, a final draft of the review report was prepared over the period December 2010 to February 2011 with the assistance of a professional science writer, Sonja Chandler. The final report was then circulated to the National Committee for Astronomy for discussion and approval and to the Australian Academy of Science for endorsement.

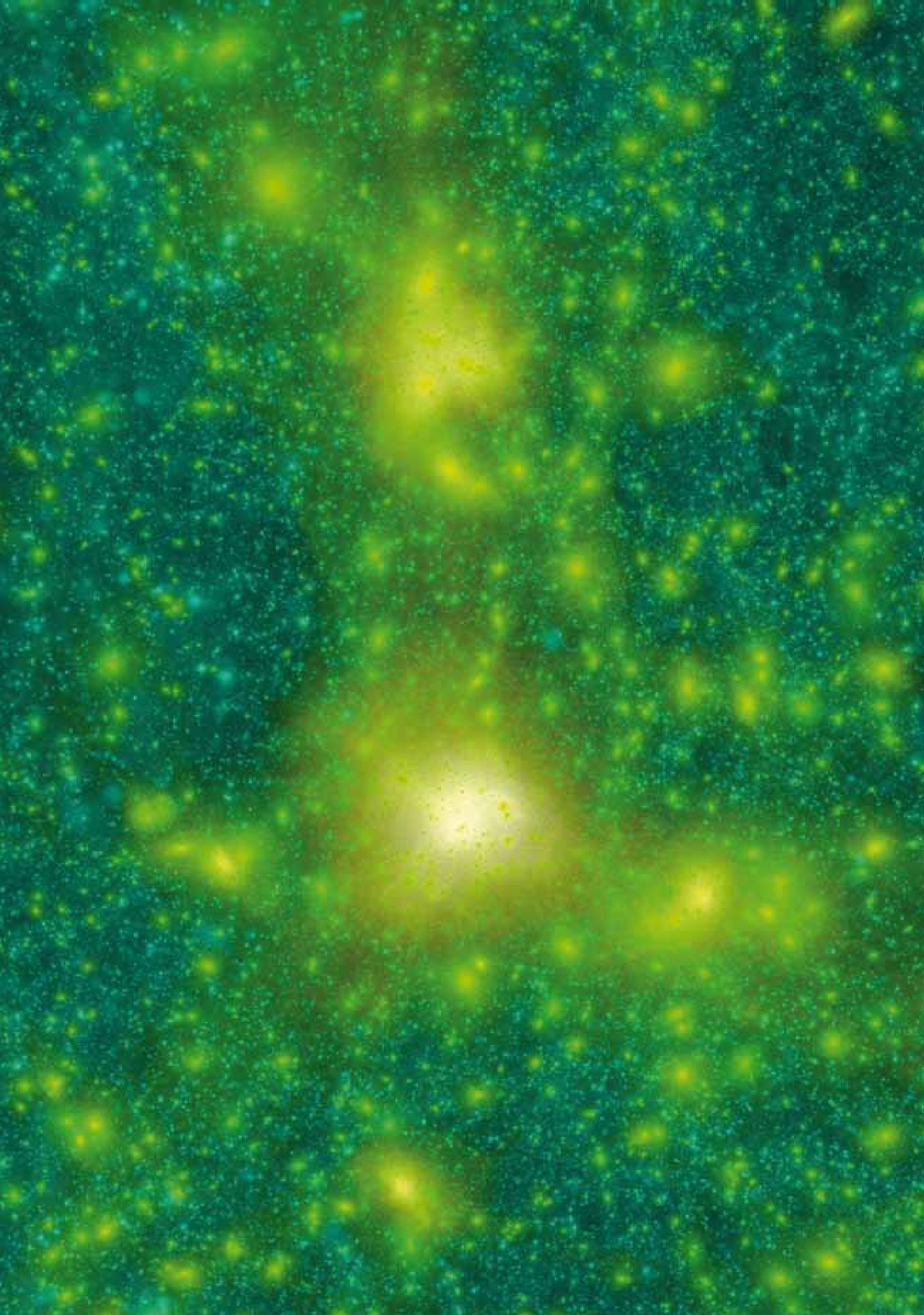
Key advisory groups

The key advisory committees who coordinated community input for the mid-term review include:

Field	Group/committee	Chair
Radio/mm Astronomy	Ad hoc Radio Advisory Committee	Professor Lister Staveley-Smith
Optical/IR Astronomy	AAL Optical Telescopes Advisory Committee (OTAC)	Professor Joss Bland-Hawthorn
	AAL/NCA ESO Working Group	Professor Jeremy Mould FAA
Antarctic Astronomy	AAL Antarctic Astronomy Advisory Committee (AAAC)	Professor John Dickey
Theoretical Astrophysics	ANITA (Australian National Institute for Theoretical Astrophysics) Steering Committee	Dr Darren Croton (convenor)
High-Performance Computing	AAL High Performance Computing Working Group (HPCWG)	Dr Darren Croton
Education and Public Outreach	ASA Council	Professor Lister Staveley-Smith

These advisory committees collated community feedback and prepared reports in response to the MTR Issues Paper. Submissions were also received from groups involved in high-energy astrophysics and gravitational-wave astronomy. The current Mid-Term Review draws on much material from these reports, which are public and can be found at www.physics.usyd.edu.au/~scroom/midterm_review





Appendix B: Glossary, Notes and References

Glossary

AAL	Astronomy Australia Limited
AAO	Australian Astronomical Observatory
AAT	Anglo-Australian Telescope
ACIGA	Australian Consortium for Interferometric Gravitational Astronomy
ALMA	Atacama Large Millimeter Array (radio)
ANITA	Australian National Institute for Theoretical Astrophysics
ANSOC	Astronomy NCRIS Strategic Options Committee
APRA	Australasian Performing Right Association
ARC	Australian Research Council
ARENA	Antarctic Research, a European Network for Astrophysics
ASA	Astronomical Society of Australia
ASKAP	Australian SKA Pathfinder (radio)
ATNF	Australian Telescope National Facility (radio) a division of CSIRO
CAASTRO	Centre of Excellence for All-Sky Astrophysics
CASS	CSIRO Division of Astronomy and Space Science
CCAT	Cerro Chajnantor Atacama Telescope
CSIRO	Commonwealth Scientific and Industrial Research Organisation
E-ELT	European-ELT (Extremely Large Telescope) (optical/infrared)
EIF	Education Infrastructure Fund
ELT	Extremely Large Telescope (optical/infrared)
ESO	European Southern Observatory
EVLA	Expanded Very Large Array
FAA	Fellow of the Australian Academy of Science
FTE	Full-time equivalent
Gemini	Gemini Observatory (optical/infrared)
GMT	Giant Magellan Telescope
GPU	Graphics processing unit

High-performance computing – a simulated galaxy cluster

GSAOI	Gemini South Adaptive Optics Imager
HERA	Hydrogen Epoch of Reionization Array
H.E.S.S.	High Energy Stereoscopic System
HPC	High-Performance Computing
ICRAR	International Centre for Radio Astronomy Research
IP	Intellectual property
IYA	UN International Year of Astronomy, held in 2009
LIGO	Laser Interferometric Gravitational-Wave Observatory
LOFAR	LOw-Frequency ARray (radio)
LUNASKA	Lunar UHE Neutrino Astrophysics with the Square Kilometre Array
MRO	Murchison Radio-astronomy Observatory
MWA	Murchison Widefield Array
NCA	National Committee for Astronomy
NCI	National Computational Infrastructure
NCRIS	National Collaborative Research Infrastructure Strategy
Pawsey Centre	Pawsey High-Performance Computing Centre for SKA Science
PILOT	Pathfinder for an International Large Optical Telescope (optical/infrared)
PLATO	The PLATeau Observatory, a self-contained site-testing facility developed by the University of NSW for deployment at remote Antarctic sites
PLT	Polar Large Telescope
PPTA	Parkes Pulsar Timing Array
PTA	Pulsar timing array
RDSI	Research Data Storage Infrastructure
SKA	Square Kilometre Array (radio)
SKA1	SKA Phase 1
SUMSS	Sydney University Molonglo Sky Survey
THz	Terahertz (frequency range 300–3000 GHz, corresponding to a wavelength range of 0.1 to 1mm)
UHE	Ultra-High Energy

Reference documents

1 *New Horizons: A Decadal Plan for Australian Astronomy 2006–2015* (including volume II, supporting information) ('Decadal Plan'), online at http://science.org.au/natcoms/nc-astronomy/decadalplan.html

2 *Australian National Astronomy Facilities – A guide for decision makers* ('Astronomy roadmap'), online at astronomyaustralia.org.au/publications.html

3 *Astronomy NCRIS Strategic Options Committee: Report to the Board of Astronomy Australia Ltd.* ('ANSOC report'), online at astronomyaustralia.org.au/ansoc.html

4 *Astro2010: New Worlds, New Horizons in Astronomy and Astrophysics*. ('US Decadal Survey'), published by the US National Academies Press and available online at sites www.nationalacademies.org/bpa/BPA_049810

5 *A Vision for European Astronomy and Astrophysics at the Antarctic station Concordia, Dome C in the next decade 2010–2010* ('ANSOC report'), prepared by the FP ARENA Consortium, online at www.arena.unice.fr

6 *The Future of eScience and High Performance Computing for all Australian Astronomers: Report by the AAL High-Performance Computing Working Group*, available online at www.astronomyaustralia.org.au/publications.html

Notes

1 The Mid-Term Review process is set out in Appendix A.

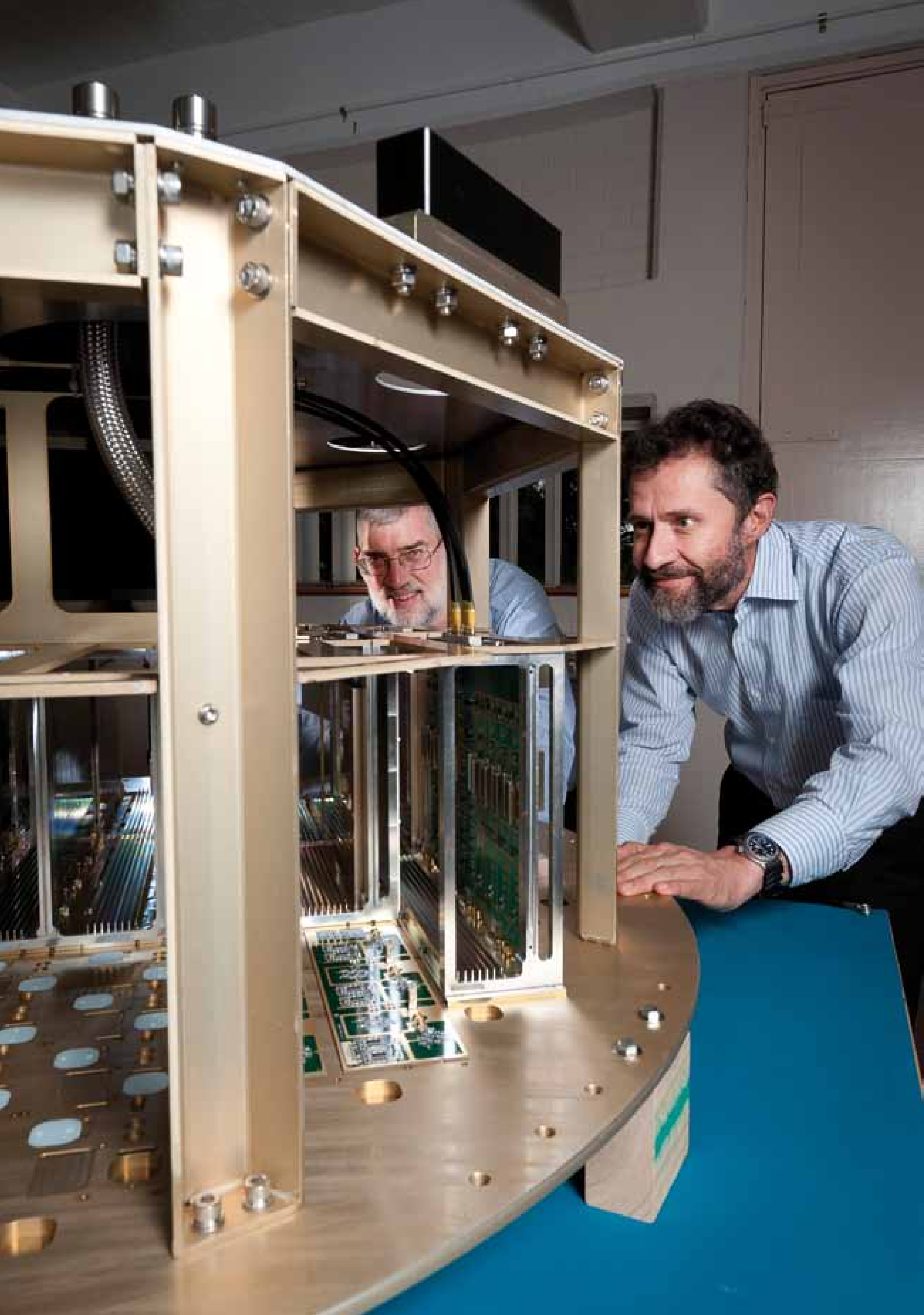
2 Abbreviations and glossary are found in Appendix B.

3 2005 Decadal Plan, Appendix: Australian Astronomy Publication and Facilities Survey.

4 Unless otherwise indicated, all A$ amounts quoted in this section are in 2005 dollars to facilitate comparison with the 2006–2015 Decadal Plan.

Credits

Opening spread:	Steven Tingay with elder Tedo Ryan at the Murchison Radio-astronomy Observatory in Western Australia. © Megan Argo.
Page ii:	CSIRO's ASKAP antennas at the Murchison Radio-astronomy Observatory (MRO) in Western Australia. © Terrace Photographers.
Page 3:	Ross Forsyth stands in the receiver cage of one of CSIRO's ASKAP antennas at the Murchison Radio-astronomy Observatory. © Ross Forsyth, CSIRO.
Page 4:	AAO technician Dionne Haynes testing a lenslet array for the Cyclops instrument for the Anglo-Australian Telescope. © Tim Wheeler.
Page 6:	AAO staff member John Collins with the mirror cell of the Anglo-Australian Telescope. © Chris Ramage.
Page 7:	CSIRO's John O'Sullivan with a prototype of the revolutionary phased array feed for the ASKAP radio telescope. © Chris Walsh, Patrick Jones Photo Studio.
Page 8:	The Gemini North telescope with its laser guide star system in operation. © Gemini Observatory.
Page 12:	CSIRO's Naomi McClure-Griffiths, in front of the 64 metre CSIRO Parkes Telescope. © David McClenaghan.
Page 16:	Jeremy Mould. © Brian Schmidt.
Page 20:	Tamara Davis. © Timothy Burgess.
Page 24:	Clancy James. © Clancy James.
Page 26/27:	Teachers' workshop on the 'Dish', CSIRO Parkes Radio Telescope. © Rob Hollow, CSIRO.
Page 28:	Engagement for all ages at Astrofest in Perth, 2011. © Pete Wheeler, ICRAR.
Page 31:	We see defence counsel Julian Burnside QC quizzing Paul Collins (in the character of Pope Urban VIII), while eminent Galileo scholar Maurice Finocchiaro (University of Nevada) and Fred Watson look on in the foreground, with members of the jury behind them. © Grant Turner, Medikoo, taken at The Re-Trial of Galileo, UNSW.
Page 32:	The Seven Sisters. © Ms Christine Collard.
Page 33:	The first public release of data collected through the Galactic All-Sky Survey (GASS), conducted with the Parkes Radio Telescope, was made in early 2009. GASS is a sensitive, fully sampled, high resolution survey and the most powerful dataset to date for studying the interaction of the Milky Way disk and halo. © S. Janowiecki (Indiana University), N. McClure-Griffiths (CSIRO), D.J. Pisano (West Virginia University) and the GASS team.
Page 34:	AAO staff member Steve Chapman, with the 3.9-metre Anglo-Australian Telescope. © Fred Kamphues.
Page 41:	Joss Bland-Hawthorn holds a prototype integrated photonic spectrograph, produced with colleagues at the AAO and Redfern Optical Components. © Chris Walsh, Patrick Jones Photographic Studio. An AAO 2007/08 AGUSS student, Emily Craven, standing in front of Gemini South. © Stuart Ryder.
Page 42:	Bryan Gaensler, University of Sydney. © Daniel Boud, University of Sydney.
Page 43:	Refilling the dewar with liquid nitrogen on the Imager of the 2.3-metre telescope at Siding Spring Observatory. This workhorse instrument of the 2.3-metre has been in use since the telescope's commissioning. This night, it was being used to observe a trans-Neptunian dwarf planet. © Michele Bannister, ANU.
Page 44:	Stefan Keller and SkyMapper – the ANU's recently completed and operational survey telescope. SkyMapper is currently producing the first digital map of the southern sky – a fundamental reference for astronomical endeavours. © Martyn Pearce, ANU Media Office.
Page 47:	This image announces a new arrival in the pantheon of exotically beautiful celestial objects. Christened 'The Red Square' for its color and form, and also in recognition of its close cousin the celebrated 'Red Rectangle' nebula, the startling degree of symmetry and level of intricate linear form make the Red Square nebula around around the star MWC 922, the most symmetrical object of comparable complexity ever imaged. © Peter Tuthill.
Page 48:	This is an image depicting the distribution of dark matter in a massive galaxy cluster. This high resolution billion-particle simulation forms part of the GiggleZ simulation suite; a large simulation program conducted by Gregory Poole at Swinburne University in support of the WiggleZ Dark Energy Survey. © Gregory Poole.
Page 52:	CSIRO ASKAP Analog Systems team leader Russell Gough and ASKAP Theme Leader and Director Ant Schinckel with the 'dry fit-up' of the Phased Array Feed being developed for ASKAP. © Tim Wheeler, Wheeler Studios.



Appendix C: Demographics

The 2006–2015 Decadal Plan recommended that there should be an increase in the number of research astronomers (and an associated increase in the number of astronomy PhD students) as new research facilities became available from 2005 onwards, noting that the total number of people involved in astronomical research in Australia remained roughly constant over the decade 1995–2005.

In July 2010, the National Committee for Astronomy undertook a short demographic survey to determine whether the anticipated growth in the size of the Australian astronomy community had occurred. While this survey was not as detailed as the much larger survey carried out in 2005 as part of the Decadal Plan, it allowed us to see some clear trends:

- the total number of people working in Australian astronomy has increased by more than 25 per cent since 2005 (from 417 full-time equivalent (FTE) in 2005 to 542 FTE in mid-2010). These numbers include people working in technical, instrumentation, support and administrative roles, but exclude PhD students
- the number of astronomy PhD students enrolled in Australian universities increased by at least 50 per cent from 2005 to 2010 (from 157 students in 2005 to 237 in 2010, excluding overseas students enrolled in the online astronomy PhD course at James Cook University)
- the fraction of astronomy positions held by women has increased slightly, from 20 per cent in 2005 to 22 per cent in 2010
- in 2010, 42 per cent of those working in astronomy were employed on fixed-term contracts rather than in continuing positions (the 2005 figure was 37 per cent).

We recommend that the Astronomical Society of Australia (ASA) should oversee future demographic surveys, conduct these on a regular basis, and keep long-term records to allow for easier and more accurate tracking of demographic trends in the astronomy community.

Acknowledgements

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