New Horizons

A Decadal Plan for Australian Astronomy 2006-2015

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Executive Summary

We live in a truly remarkable time. As our understanding of the Universe deepens, we are seeing connections emerge between many formerly disparate fields of research. Astronomy, and Australian astronomy in particular, can boast some of the most remarkable discoveries in recent years, including the detection of planets around other star systems, the discovery of unique astrophysical systems such as the double pulsar, and the detection of a mysterious “dark energy” that pervades our Universe and opposes the relentless pull of gravity.

Astronomy targets the biggest questions it is possible to ask. It explores the fundamental nature of science on scales and in realms too extreme to examine in any laboratory. Ultimately, it is through astronomy that we will understand the emergence of life within the tapestry of planets, stars, dust clouds, and galaxies of our Universe. It is through astronomy that we will understand how this emergence is linked to the fundamental laws governing the origin, evolution and final fate of the Universe itself. Over the next two decades, the international astronomical community will build the largest radio and optical telescopes ever constructed as they seek to answer these questions.

This Decadal Plan presents the Australian astronomical community’s strategic vision for our continued engagement with this great adventure. It maximizes astronomy’s benefit to the nation by:

- continuing and enhancing our capacity to undertake world-leading research;
- training a new generation of graduate and postgraduate students in science and engineering;
- stimulating our capacity for innovation in science and engineering;
- and, perhaps most importantly, inspiring and educating the public at large.

As one of our nation’s highest impact sciences, Australian astronomy’s outstanding track record in each of these areas has been, and will continue to be, based on a suite of strategic investments in both national and international infrastructure, and in the people who turn such facilities into research outcomes. The nation’s areas of internationally acknowledged strength — as measured by capability, global impact and natural resource —are targeted as high priorities: ground-based astronomy at optical/infrared wavelengths, astronomy at radio wavelengths, and theoretical astrophysics.

Over the coming decade 2006 – 2015, international astronomy will continue a trend toward increasingly global projects and collaborations. This Decadal Plan outlines how Australian astronomy will continue and expand its engagement in such projects, while developing unique Australian scientific and knowledge-base capabilities that will leverage access to other facilities (e.g. space-based facilities) that lie outside the nation's direct scope.

The elements of this strategy are

International Leadership – Playing a key role in next-generation facilities by hosting them on-shore.
International Partnership – Engaging fully in consortia building next-generation facilities at the world's best sites.
Forefront Technologies – Leveraging maximum return by early engagement in the relevant technologies.
Education and Training – Creating the best training environment and career structure in the 'enabling sciences' of physics and mathematics; in turn providing the essential underpinning of national innovation.
Outreach – Communicating the results of research to the public, especially children, in an exciting and accessible way.

In both the optical/infrared and radio domains, the international astronomical community will bring the next generation of major infrastructure to fruition after the end of this Decadal Planning period. In preparation for this, engagement in both an optical/infrared Extremely Large Telescope and the Square Kilometre Array radio telescope program at a level of at least 10% is the highest-priority long-term goal to maximize Australia's science impact and technology return.

Australia's engagement in the Square Kilometre Array program will be most effectively directed towards the development of new radio astronomy infrastructure in Western Australia, leading to the development of a major pathfinder facility by the end of this decade. In the optical/infrared domain, Australia will obtain maximum benefit from Extremely Large Telescopes by continuing its development of innovative optical/infrared instrumentation for national and international telescopes, by increasing its share of 8m-class telescopes to the equivalent of a 15 – 20% partnership and by continuing to explore opportunities associated with its Antarctic sites. In these technology-intensive developments, Australian astronomy will continue to enhance its engagement with industry in order to maximise technology diffusion.

Together, the Square Kilometre Array and Extremely Large Telescope initiatives will form the long-term "backbone" which drives a ramped-up investment in facilities and people over the coming decade via a staged process. A key component of this investment is ongoing support for the National Facilities, University-run facilities/experiments and the observational and theoretical research programs that motivate this infrastructure. This support is essential to train and develop the generation of scientists and

engineers required to build and exploit its infrastructure. Engagement in the international Auger cosmic ray experiment and the Advanced Laser Interferometer Gravitational-Wave Observatory consortium is also seen as important to capitalise on Australia's unique knowledge in these domains.

During the Decadal Planning period, the Anglo-Australian Observatory and the CSIRO Australia Telescope National Facility will play an increasing role as National Observatories, coordinating and managing involvement in both national and international facilities. This will enable a national approach to the broader provision of research support and the potential to reprioritise operational funds to new programs.

During the first five years of this plan the required level of new investment is approximately AUD50m. Over the decade, indicative new investment levels in Australian astronomy implied by this Decadal Plan amount to approximately AUD125m. Any new investment over the next ten years will be supported by the reprioritisation of AUD50m existing operational funds to meet investment goals in new infrastructure.

Over the past decade the Australian astronomical community has demonstrated the ability to formulate a strong vision, prioritise its goals and deliver on its promises. This Decadal Plan is an extension of our vision to 2015 and is an expression of our commitment to deliver the best possible outcomes for Australian astronomy and the nation.

Preface: New Frontiers for a New Decade

Astronomy is a profound expression of humanity's need to understand how the universe works. The questions astronomers seek to answer are amongst the most fundamental in science. As the full complexity of the cosmos becomes apparent, today's astronomers require cross-disciplinary skills in fields as diverse as computer modelling, chemistry, fluid dynamics and even biology.

We are living through a remarkable era of discovery. For the first time we have found clear evidence for planets circling other stars, for massive black holes occupying the centres of many galaxies – including our own, and for a dark energy component to the Universe whose origin and nature we have yet to fully understand.

Astronomers are able to test the fundamental laws of physics on scales and in realms too extreme to examine in any laboratory. Over the coming decade, astronomers in Australia and around the world will be targeting basic and fundamental research into some of the biggest questions it is possible to ask.

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

> One of the great puzzles of modern cosmology is that up to 95% of the Universe apparently consists of dark matter and dark energy, whose physical nature is unknown, and which we can only observe indirectly by measuring their effects on visible stars and gas. Determining the nature of these dark components of the Universe is an important problem in fundamental physics.
>
> The existence of dark matter was first suggested more than twenty years ago, but the dark energy has only recently been deduced from observations of distant supernovae explosions, which show that the expansion of the universe is speeding up. There are many possible forms this dark energy could take, and detailed observations are needed to distinguish between competing models. Over the next decade, measurements of very large numbers of standard candles (e.g. supernovae) or standard rulers (e.g. the scales on which galaxies cluster) in the early Universe are needed, and new wide-field optical and radio facilities have been proposed to tackle this problem.

Is Einstein's theory of gravity correct?

Nature's most accurate clocks are pulsars – the rapidly rotating collapsed remnants of massive stars. Pulsars have enormously strong gravitational fields, and provide a unique laboratory for testing theories of gravity under conditions that are impossible to probe in Earth-based laboratories.

Physicists are currently developing theories of quantum gravity, which unify theories of gravity and quantum mechanics and attempt to describe all the known particles and interactions of the physical world. Some of the most stringent tests of these theories come from observations of pairs of pulsars that orbit each other, and especially from the (as-yet undiscovered) binary systems in which a pulsar orbits a black hole. These systems are rare, but provide crucial tests of the fundamental nature of general relativity and gravity. A network of pulsars spread over the sky could also be used to make the first detection of gravity waves.

How and when did the first stars form in the early Universe?

The very early Universe, as revealed by observations of relic radiation from the Big Bang, was almost completely uniform in density. This is in complete contrast to the Universe we see today, which is complex, inhomogeneous and full of stars and galaxies.

At some point in its first few million years, the Universe must have undergone a fundamental transition in structure powered by the first objects to be formed. When, where and how did the first stars form? How massive were they? And how did they subsequently influence the evolution of the universe?

How are galaxies assembled and how do they evolve?

There is growing evidence that large galaxies like our own Milky Way are assembled over cosmic time by successive mergers of smaller galaxies. Their history is therefore likely to be complex, with bursts of star formation associated with the swallowing of each small galaxy or gas cloud rather than a smooth transformation of gas into new stars over time. Much progress has been made in tracing the global rise and fall of star formation in galaxies over the last 90% of the history of the universe, and a general "cold dark matter" framework exists for understanding the growth of structures, but critical uncertainties remain.

In particular, how do the interactions of galaxies affect their eventual

shape and brightness, and how do the small, clumpy galaxies we see in the early Universe evolve into the high-structured systems seen today?

What is the origin and evolution of cosmic magnetism?

Magnetic fields permeate the Universe, and span an enormous range in strength, from the weak magnetic fields in interstellar space to the extremely strong magnetic fields of pulsars. They play a key role in the physics of star formation, control the density and distribution of cosmic rays within our Galaxy, and collimate the powerful radio jets that emerge from super-massive black holes at the centres of radio galaxies. Although magnetic fields are intimately involved in astrophysical processes on many scales, the origin and growth of magnetism in the universe is poorly understood at present. When and how did magnetic fields form in the early universe, and how does this relate to the formation of galaxies and large-scale structure at the same epoch?

How do stars and planetary systems form?

Stars form when regions of the interstellar gas clouds in galaxies become gravitationally unstable, and collapse to densities and temperatures sufficient that nuclear fusion reactions begin. In order for these turbulent and diffuse clouds to collapse to such small sizes, they must redistribute their angular momentum. They do this via accretion disks – churning maelstroms that swirl around forming stars, and which transport gas and dust inwards from extended gas clouds onto the proto-star's surface. And inside these accretion disks, agglomerating dust particle grow into the rocky nuclei of terrestrial and gas giant planets.

While this general picture is accepted, the details of several critical stages in remain murky and poorly understood. How *exactly* does turbulence in accretion disks dissipate angular momentum, and what impacts do magnetic fields have? How *exactly* do dust particles grow into the rocky planetismals that build planets? What impacts do these processes have on the global rate at which gas and dust are turned into stars?

How common are planetary systems and conditions suitable for life?

The detection over the last decade of numerous planetary systems outside our Solar System, has been one of the most significant astronomical outcomes of the century. We now know that gas giant planets are, if not common around other stars, at least not rare. We also know that the "ecologies" of planetary systems are many and varied – indeed few planetary systems are known that look even remotely like our own.

Most critically, then, in the next decade astronomers will seek to find out how common planetary systems are in all their many configurations. And in particular, how common are systems in which rocky, terrestrial planets are suitably placed for the evolution of the types of life we see on the surface of our own home – that is, how many Earth's can we detect orbiting around nearby stars?

How do stars produce and recycle the elemental building-blocks of life?

Understanding the life and death of stars, and the birth of the subsequent generations from ashes of those stars that have gone before, is a fundamental part of the quest to understand the processes that generate life.

When stars about the mass of the Sun reach the end-stages of their lives, the products created through internal nuclear reactions are transported to the surface and ejected into the interstellar medium. Stars more massive than the Sun, and certain types of binary stars, undergo more violent deaths as supernovae explosions. In both cases, the enriched material of each star's core, becomes available for the formation of new generations of stars and planets. Understanding the details of this enrichment cycle is fundamental to our understanding of the frequency with which habitable planets can form throughout the universe.

1. Australian Astronomy 2005

Australia has a long and proud tradition in astronomy. For the past 50 years, Australian astronomers have been at the forefront of their field. Today, it is one of the nation's highest impact sciences[1]. Australian astronomers have pioneered some of the most important technological advances in astronomy of the past two decades; including the use of fibre-optics and robotics in astronomy and advanced signal processing techniques.

In order to understand the physical processes occurring throughout the universe, it is essential to use a wide variety of tools. The study of cool, low energy processes is best done at radio wavelengths, while hot, energetic objects including stars are more accessible via optical/infrared or even x-ray telescopes. The signals from this "cosmic symphony" that span the entire spectrum from low-frequency radio waves to high-energy gamma rays cannot be decoded by looking at sections of it in isolation. For this reason, every successful nation in astronomy exploits a range of observing facilities across the electromagnetic spectrum. Particle astronomy and gravitational wave physics are also helpful in forming a complete picture of the universe.

Australia has been successful due to the significant investments in world-class and innovative research facilities that have been made since the 1960s – making it possible to attract and retain excellent researchers. Our major optical/infrared facilities include the Anglo-Australian Telescope and the Gemini telescopes in Chile and Hawaii. At radio wavelengths, the single-dish radio telescope at Parkes and the multi-antenna Compact Array at Narrabri are our most powerful facilities. Combined with university-operated observatories, supercomputing facilities and an effective national information technology network, Australia has a solid base from which develop its capabilities into the next decade.

As important as these facilities are, the people who use and exploit them – turning data and theoretical models into scientific outcomes – are just as critical. The number of Australian astronomers has remained constant over the past decade[2] in contrast to the decline in other braches of physics and this has been an important factor in maintaining Australian astronomy's international impact.

[1] At A Glance 2005, DEST report
[2] Demographics Working Group Report
[3] International Facility Working Group Report

Australia's key observational strengths lie in the radio and the optical/infrared domain. Optical and radio astronomy account for over three-quarters[3] of the total citations gathered by Australian astronomers over the past decade. Of these citations, approximately half derive from Australia's national facilities, and a quarter each from Australian university-run facilities and overseas facilities funded by other countries.

One fifth[4] of Australia's astronomy graduates move into commerce and teaching, making an important contribution to the nation. A university training in astronomy develops critical skills that are highly valued in the commercial and industrial sectors, with the result that astronomy-trained graduates can be found in many senior positions in information technology, banking, industry and defence[5].

Most important of all, astronomy plays an important role in inspiring young people. Astronomy is being seen by educators as a valuable context within which students can be taught a range of scientific subjects. Victoria and NSW have both recently introduced astrophysics into their senior high school physics curriculum. Strong astronomy groups at our universities and national observatories are working to ensure that more of our best young people develop an interest in and an understanding of science, without which the nation cannot hope to remain technologically competitive.

Astronomy has always received the strong support of the general public. Fundamental research at the frontiers of science is an essential cultural element of any technologically advanced nation and an important expression of our identity. Australians are justifiably proud of our position as one of the world's most successful nations in this field.

To maintain this position, Australia needs to make some wise decisions.

This Decadal Plan is the result of a priority-setting exercise that reflects the ability of the astronomical community to make these decisions; working together cooperatively in the formulation of a strategy for investment that is in the best national interest.

[4] Education Working Group Report
[5] People Case Study
[6] Education Working Group Report

2. The Foundation of Astronomy: Education

Astronomy, like other sciences, is directed at the discovery of new knowledge about the universe, and the dissemination of this knowledge amongst both astronomers and the public. Because its scope is so large – addressing questions that are fundamental to our existence – it is one of the most popular and accessible sciences. The teaching of astronomy,and the general diffusion of astronomical knowledge, are important contributions that astronomers make to society at large and to the health of science and technology in particular. The professional training of astronomers is fundamental to the development of the subject, but many citizens learn about astronomy at various levels and in various ways. Any level of exposure to an exact science is valuable in maintaining a scientifically literate society and in encouraging young people to persist with study in scientific subjects. Astronomical education is part of education in its widest sense, which is a life-long endeavour.

Astronomers play their part in public education, mostly as volunteers during open days or viewing evenings, or by giving public lectures to clubs and societies. Over the past five years, on average a public lecture has been given by an astronomer once a fortnight and 50000 people a year have attended a free public astronomy event[6]. This compares well with the attendance level of half a million people per year at Australian planetariums. Outreach activities can be difficult to support when budgets are tight, and it would be desirable for research grants to be enhanced, in a directed way, by the very modest percentages that would sustain and increase this commitment to public education.

Astronomy is part of the school curriculum (both primary and secondary) across Australia, and because of its exciting content is often used to stimulate interest in science. However a declining proportion of teachers is qualified in any area of the natural sciences, and this is inevitably reflected in a steadily-falling number of students who study physics, chemistry or mathematics. Astronomers cannot solve this nationwide problem on their own. However, the maintenance and development of programs of public outreach, especially those that support teachers, is an important activity for astronomers. Much of what is done is again unfunded and voluntary, but would benefit from more coherent support within national and state programs[7].

At the undergraduate level, many universities now teach astronomy modules within physics programs (including to non-science majors), with about 250 lectures per year being delivered. For many students this is the only science course they attend at university. Within physics, astronomy sets a useful context for the study of topics such as gravitation, radiation transfer, or

[7] Education case study (ATNF education officer)

computational physics, and is also attractive to students because of the general fascination of astronomy. Six Australian universities offer honours degrees in astrophysics, and most graduates of these programs progress to a research degree in astronomy, with about one-sixth moving on to careers in industry or teaching. Since a physics degree provides excellent training for a range of scientific and analytical careers, the community should continue and increase its commitment to undergraduate teaching.

Astronomy is a growing component of science education in countries in the region, especially South East Asia. Undergraduates tend to be extremely well trained in these countries and are attractive as PhD students in Australia, where they can make a considerable contribution to Australian science before graduating. Currently the fee-exempt awards for such students are few in number, and could be increased to the benefit of Australia and our neighbours.

The PhD program is the backbone of professional astronomical training in Australia and about twenty doctorates are awarded per year at present. About a fifth of these go on to careers in teaching or industry, and the remainder take up post-doctoral research appointments in Australia or overseas. At present, the number of PhD students is a steady and reasonable proportion of the research community (about a quarter) and should be maintained at this level or above. There are two reasons for increasing the number of PhD studentships. First, as new facilities become available during the decade, there should be an associated modest increase in the number of research astronomers in Australia, with a proportional increase in PhD places. Second, the development of these new facilities should include a vigorous involvement of Australian industry, and as a consequence a greater proportion of PhD graduates may be expected to find their skills in demand in this sector. The national facilities already play a role here through the joint supervision of PhD students, and there is an opportunity to increase the scope of such programs.

In an increasingly competitive world, it is vital that Australian graduates are trained to the highest possible standards. The development of high-bandwidth communications is making the virtual classroom a reality, and it is now possible for graduate courses to be distributed across Australian universities. This means that graduates can be taught by the national expert in any given subject. While there are practical and administrative difficulties to be overcome, attaining this ideal should be an objective for astronomy educators within five years. Additionally, the vital interaction provided by attendance at workshops and conferences should be programmatically supported.

3. A Strategic Plan for the Next Decade

3.1 Introduction

Two related features dominate planning for next decade – the remarkable breadth of opportunities that lie ahead of us, and the increasingly international nature of modern astronomy. Astronomy now spans the electromagnetic and particle spectrum. Areas of astronomical research are now defined by their intrinsic physics, chemistry or biology, rather than by their earlier delineations due to accidents of technology, geography or the transparency of our planet's atmosphere.

Both features have had increasing impact in recent decades, and pose challenges for Australian astronomy. To retain its world-class position, Australia will have to strengthen further its domestic research capacity while continuing its transition into a world of major international programs, agreements and commitments. Our astronomers have long worked internationally, and are increasingly successful in collaborating with overseas scientists[8]; the time has now come for similar internationalism on the scale of inter-government and inter-agency agreements.

The current health of Australian astronomy represents the dividend of far-sighted investments – many made a decade and more ago. For similar future success it is essential that comparable investments are planned for and made over the next decade. Otherwise, Australia faces the threat of losing ground to other nations in access to state-of-the-art telescopes and experiments.

3.2 People – Australia's most valuable scientific asset

Major radio and optical telescopes are the end point of years work by many people. While much of the emphasis of this Decadal Plan is on projects, it must be recognised that proper support of the people involved and the processes of research management are critical.

While the nation has geographical advantages in its natural resources like the radio-quietness of inland Australia and excellent observing sites of the Australian Antarctic Territory, these are of little value without the expertise of its astronomers and engineers, both students and professionals. This expertise allows Australia to be disproportionately successful in gaining access to many facilities funded by other countries, winning overseas instrumentation contracts, and participating as intellectual equals in projects involving much bigger players.

[8] Internationally co-authored publications have increased from 55% to 77% over the last 10 years. *A Bibliometric Analysis of Astronomical Science Publications*, Biglia and Butler, May 2005

It is vital for education and training in astronomy to be ambitious and effective. It is also important that human resources are efficiently used. The great majority of research in astronomy is carried out in universities. Over the span of this decadal review, there will be at least one, and perhaps several, quality assurance initiatives in publicly-funded research and education. Part of the prudent spending of public money is that scarce resources should be used to greatest effect, and any assessment of the quality delivered by scholars should also ask explicitly whether scholars' time is being wisely divided between teaching, research, administration, and the securing of funding. These are systemic issues in which the decisions of the most powerful stakeholders in research – government and universities – can have profound influence.

Investment in people must parallel investment in facilities. While large infrastructure projects often command the greatest attention, it is clear that careful planning must be put into how these facilities will be developed, used and enhanced throughout their projected lifetimes, along with an eventual plan for decommissioning. The international-scale projects planned for the next decade will require dedicated teams to provide the scientific direction to their development and operation. Attached to any of these major projects, therefore, must be an adequate number of research support positions, comprising first-class scientists who apply their research-based experience to the practical support of the facility. These could be constituted as fixed-term post-doctoral fellowships and non-continuing staff positions, along the lines of the model that has been so successful in the operation of the AAO and ATNF. Some of these positions might be implemented as high-prestige named fellowships at any institution in Australia.

Theory is one important area of astronomy where the role of people is pivotal. Theorists pose many of the questions that drive the next generation of large facilities, and often lead the interpretation of the results. Successful teams of theorists have tended to emerge from an indirect process, such as a cluster of teaching appointments, successful grant applications and the like. A more strategic approach to planning for theory will be required over the next decade as Australia moves increasingly into very large infrastructure programs on international scales. These projects will contain experimentalists and technologists who should also interact with strong theory groups either inside or outside the facility.

These theorists should play an important role in guiding the development of the scientific specifications. The distinctive analytical skills of theorists can be of benefit to the solution of the many intricate design problems (e.g. adaptive optics) that the next generation of projects will entail.

3.3 Governance – Managing Australian Astronomy

At present there are no established mechanisms via which Australia can make commitments on the scale that the coming generation of international astronomical facilities command or provide an executive body with the authority to implement that commitment. The funding and evaluation mechanisms in Australia are primarily bottom-up, depending on the success of individuals or groups in securing grant-based funding through a variety of routes. The funds available are usually short-term and are rarely, in any one grant, sufficient for participation in projects of the scale of the next decade. As a result, current procedures mean that Australian astronomy, despite its potential collective strength, cannot operate internationally with any more weight or authority than a university department with a few-year horizon.

While there are great advantages in this market-led style of funding, the ability to develop and maintain strategic direction is not one of them. The scope and duration of the next decade's projects require that Australia develop mechanisms for negotiating and committing, both nationally and internationally, over time-scales of five to ten years. These are the lead times for the staged development of the giant telescopes that will be completed in 2015 – 2020, and they are the timescales over which the health and productivity of Australian astronomy can only be assured by access to the peak international collaborations and facilities. This cannot be achieved by short-term expedients, which inevitably lead to Australia's marginalization by international partners who are prepared to accept full levels of commitment and risk.

Executive bodies are needed to engage with the Commonwealth on a whole-of-government basis, to negotiate with national and international partners and ultimately to manage the major astronomical initiatives of the next decade. In their capacities as national observatories for optical and radio astronomy respectively, the AAO and CSIRO-ATNF are well placed to deliver this service. These existing national facilities can do so with only a small additional administrative load, while remaining strongly consensual in their mode of operation. Both aspects are essential given the nature and size of the Australian astronomical community.

3.4 Astronomy and Industry – Maximising our investments

An important area where a more integrated approach is needed is in the relationship between astronomical research and industry. Astronomical technologies can have very important spin-offs into other areas, as demonstrated by the foundation and success of Radiata in the communications area, or Auspace in the area of satellite integration. Both of these companies have roots in astronomical research. In general, astronomy is funded as a research, education and training enterprise and not primarily as a method of stimulating innovation in industry.

Innovation policy is a complex area. Much innovation in successful businesses is incremental in nature and owes little – at least in the short term – to basic research. However, what is clear is that it is important to ensure that innovation of potential commercial value, which does occur in a pure research context, is captured and exploited. Most astronomy is done in universities, which have well-developed processes for identifying intellectual property and protecting it. However, this process often makes only indirect contact with the needs and interests of industry. There are several industry associations (AEEMA, AIIA) and networks of companies, both in the commercial and defence sector, which have a commercial interest in areas of technology that astronomers need or develop. Strong interaction with these networks and associations must a be high priority for the recently-formed Australian Astronomy Industry Network.

This will encourage knowledge diffusion and the use of innovation; it will also increase the opportunities for astronomers to use Australian suppliers in preference to overseas ones. Associated with the major projects of the forthcoming decade, there should be specific resources identified to maintain databases of relevant industries, to keep industrial and astronomical stakeholders informed of each others' relevant activities, and to identify and nurture opportunities for commercial exploitation.

3.5 Current and Future Facilities – an Astronomical Pyramid

3.5.1 Current facilities: Universities

Australia's current and future suite of facilities can be viewed as a pyramid. At the apex are the small number of major international programs in which Australia collaborates with other nations to build and operate facilities too large for any one country. At the level below sit the national facility organizations who both operate major facilities based in Australia, and have the capabilities to manage Australia's access to, and complement the research of, large-scale international programs. Forming the foundation of the pyramid are university research groups who run a broad suite of small facilities.

University facilities have a comprehensive range. They are important for training, for development of technologies, and for speculative observing programs[10]. University operated experiments in cosmic-ray and gravitational-wave physics are particularly important in their own right. Funding for these facilities tend to be short-term or episodic. University facilities produce a wide

[10] University facilities have been responsible for one sixth of all astronomical citations gathered by Australian astronomers over the past decade. *International Facilities Working Group report*

range of research which stands on its own merits, both nationally and internationally – indeed it is required to due to the peer-reviewed routes via which funding is typically acquired.

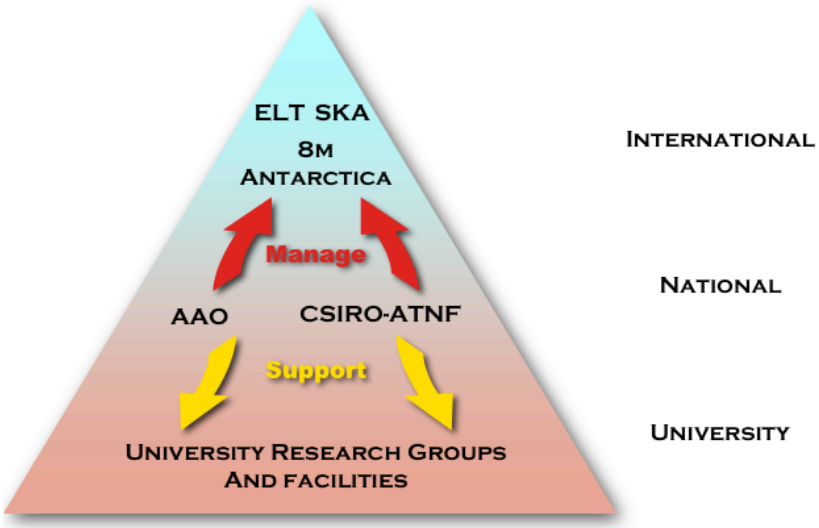

Figure 3.1 The Astronomical Pyramid[11]

The reliance on grant funding for the operation of university facilities is a double-edged sword. Most funding mechanisms are oriented towards short-term innovation, rather than long-term operational or development costs. This has caused serious continuity problems where astronomical experiments and facilities are operated on timescales of more than just a few years. The resulting inefficiencies are a drain on the community financially and a significant opportunity cost for some of the nation's most productive scientific facilities.

A specific example is the Siding Spring Observatory (SSO), operated and funded by the Australian National University (ANU). This facility provides open access to its telescopes to astronomers across the country, and its telescopes are widely used by astronomers outside the ANU. Due to the partial transfer of ANU's block grant to programmatic funding, ongoing support funds are no longer adequate to support the existing suite of telescopes. Maintaining the community's access to the ANU 2.3-m telescope has been identified as a priority for the next five years.

[11] Note that we classify facilities as International, National and University based on their scale, rather than their membership. Both at the national and university level, several facility partnerships involve international partners, but are not classified as International due to their smaller scale.

A possible mechanism for providing ongoing funding for the operation of university facilities is the modification of existing grant arrangements to provide “rolling grants” with an appropriate critical review at least 12 months before the renewal of the grant

Australia has an excellent record of achievement in air-shower astronomy, the study of very high energy cosmic rays. These projects have a large international dimension. The projects are Australian participation in the Pierre Auger Observatory, in Argentina, and the CANGAROO Project at Woomera. More effective Australian activity in these projects should be supported through the rolling grant mechanism discussed above, mindful of the strategic issues associated with international collaboration.

3.5.2 Current facilities: National

The 3.9m Anglo-Australian Telescope (AAT) is the single optical/infrared national facility for Australian astronomers. It is currently funded jointly by Australia and the UK. It is located on the SSO site, providing added emphasis to the need to develop a viable long-term plan for that site.

By 2007 the AAT, and its parent organization, the Anglo-Australian Observatory (AAO), will be 87% Australian-funded, while by 2010 it will be wholly Australian-owned. The telescope will continue to be a world-leader in survey astronomy for at least the next five years, and beyond that will be critical as the single biggest source of optical/infrared observing time to Australian astronomers. During the decade, at least one more major instrument will be needed to maintain the telescope’s scientific competitiveness. It is clear that by the end of the current decade the role of the AAT will have changed considerably, though the operational lifetime of the telescope will depend on whether more access has been obtained to 8-m class telescopes and will also on the progress towards Australian participation in an Extremely Large Telescope.

The future of the AAO is a separable issue from that of the AAT. The observatory will have a clearly-defined role while the AAT remains operational. Beyond that, it will continue to play an essential yet evolving role as described below. The instrumentation program at the AAO is one of the very best in the world and it should be retained and developed as a national asset. Along with technology development in the universities, it will be a key factor in allowing early engagement and influence in the next generation of telescopes, and is an important source of intellectual property.

Moreover, during the next decade, the scale and complexity of Australia’s external involvement in major international facilities will expand (e.g. Gemini, Antarctica, and Extremely Large Telescopes). In its role as the optical/infrared National Observatory, AAO will also be able to negotiate with international partners in the next generation of optical/infrared facilities, and

ultimately to manage Australia's access to these facilities by acting as a national project and facility support organization.

In the radio, the telescopes of the Australia Telescope National Facility (ATNF) continue to be highly productive in addressing a wide range of astrophysical problems. The extent to which these telescopes can replaced and resources redirected to new infrastructure will largely depend on progress made with the prototypes for the Square Kilometre Array (SKA), the highest priority new program for Australian radioastronomy. Over the next five years the Parkes and Mopra telescopes are expected to be vital contributors to the community's research, while the Compact Array will continue to have an important role over the whole decade.

CSIRO, the managing organization for the ATNF, is well placed to act as the governing body for Australian SKA activities and the contracting body for the international program. As the radio National Observatory, the ATNF will manage Australia's access to the international SKA pathfinder and eventually to the SKA itself.

3.5.3 Information and Communication Technology Infrastructure

The success of future astronomical research will depend on greatly increased computational power, data storage, and connectivity. Supercomputers are necessary for many types of theoretical modelling, data collection and analysis relies on extremely fast on-line processing, and storage of the results requires archives measured in Petabytes (10^{15} bytes). Sustained and significant investment in all these areas is essential. Some of this may be achieved through national supercomputing facilities and some through university facilities. Increased bandwidth (up to 100 Gigabits/sec) should be provided by AARNet before the end of the decade.

Approximately 50% of theoretical astrophysics research in Australia utilizes advanced computation on state of the art computational facilities. These facilities can be easily centralized and shared across a wide range of sciences, so that the initial capital cost and subsequent upgrades, maintenance, and depreciation are spread over a diverse range of scientific programs. The existing supercomputing centres should continued to be supported at the levels required to provide the infrastructure needed to support astrophysics. The community should have access to an internationally competitive supercomputer (within the top 50 in the world).

High-bandwidth communications will assume even greater importance shortly, when grid computing and Access Grid communications become common. This will greatly enhance collaborative activities across the research community.

Australia should to continue to participate in the International Virtual Observatory Alliance, a worldwide facility that aims to collect the archives of the world's major observatories into one distributed database. This activity will help to increase the worldwide impact of data taken with Australia's own

telescopes and provide Australian astronomers with access to data from other telescopes world-wide.

3.5.4 Current facilities: international

Australia currently participates in the twin 8-m Gemini Telescopes at a 6.3% level; corresponding to a 12.6% access level to a single 8m-class telescope. Support from the MNRF will yield additional time on Gemini (up to a total of 20% 8m-access) over the next two years. Excellent research is being done, and Australians have been extremely successful in winning instrumentation development contracts from Gemini[12].

This level of funding for 8m-time needs to be continued over the decade – not only to exploit the new science opportunities wrought with new instrumentation being built or developed by the Gemini partnership (e.g. NIFS, GSAO-I and GWFMOS) but also increasing the community's access to a broader suite of instruments potentially on a variety of 8m-telescopes relevant to Australia's scientific strengths. This will enhance and enable a very wide range of research and improve training opportunities for students. This facility, or group of facilities, would sit at the apex of a well-proportioned Astronomical Pyramid.

There is an urgent need to streamline Gemini funding arrangements. The current funding mechanism is a combination of MNRF, LIEF and University contributions, which is awkward, time-consuming and a tax on the whole research community's capacity for innovation.

Since all the relevant 8m-class telescopes are offshore, attaining these objectives will require a more strategic and streamlined method of negotiating and contracting internationally as discussed above.

3.5.5 Future projects: Growing the Pyramid

There are many ambitious astronomical projects now in the planning and design stage. Some of the largest are space missions, predominantly being undertaken by NASA and the European Space Agency. On the ground, the largest new astronomical program is the Atacama Large Millimetre Array (ALMA); a collaboration between US, Europe and Japan. Australia cannot be a direct participant in these, but, with proper investment in our areas of strength, we will continue to contribute to, and benefit from, these missions as valued collaborators with international astronomers[13].

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[12] Innovation Case study (Gemini instrumentation/GWFMOS)

[13] One-third of Australian citations over the past decade have come from the use of international ground-based or space-based facilities that Australia is not a direct participant in. *International Facilities Working Group Report*

Two of the pillars of Australia's present reputation are its radio and optical/infrared observatories[14]. On an international scale, both of these areas will see the development over the next decade of very much larger telescopes than are presently available to any astronomer. Radio astronomers world-wide are planning a staged progress towards the Square Kilometer Array (SKA), which, as its name suggests, will have a very much larger collecting area, and hence greater sensitivity, than any present-day telescope. Because the SKA is a technically ambitious project, its staged development includes various national prototyping projects (in Australia, called NTD and xNTD) and an internationally-funded "SKA pathfinder" which is planned to follow on from the national efforts. This staged process, each stage resulting in a unique scientific capability in its own right, is part of a comprehensive risk mitigation approach to the SKA program. Over the decade, increasing amounts of operational resources for current infrastructure will be reprogrammed into the development and operations of these SKA prototypes. By the time the SKA is commissioned, most operational resources for the current national radioastronomy infrastructure will have been re-directed into SKA; meeting in full Australia's long-term operational commitment to the SKA.

In the optical/infrared, the international scene is more complex, with several projects under way to develop Extremely Large Telescopes (generically known as ELTs). The European "OWL" project is the most ambitious, aiming at the construction of a telescope of 100m aperture. Likely to arrive sooner are two projects based in the United States, the Thirty Meter Telescope (a largely Californian project, with Canadian participation) and the Giant Magellan Telescope (a consortium of major US universities, with Australia currently participating as an observer).

A much smaller project, but of considerable long-term significance, is the Australian-led PILOT consortium, which aims to operate a small "pathfinder" telescope on the high plateau in the Australian Antarctic Territory (Dome C). While the operational issues to be overcome at this site are challenging, there are compelling indications that the Antarctic is the best optical/infrared astronomical site on the planet by a very wide margin. Looking ahead a couple of decades, it may well be possible to place a large telescope there that will out-perform 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.

Both the ELT and SKA scenes are complex, as yet no project is more than partially funded. The site choices for the telescopes have not yet been made, and the partnerships are fluid. In addition there are considerable technological challenges attending the design and construction of such large instruments. However, solving these challenges is also the lifeblood of innovation.

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[14] 45% of Australia's citations over the last ten years have come from AAO, ATNF + ANU optical/radio observatories. *International Facilities Working Group Report*
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Because of the compelling science case for these telescopes, Australian astronomy has set an ambitious yet achievable target of participation in both SKA and an ELT. Radio and optical/infrared astronomy, and the associated areas of astrophysical research, are a key strength of the community; it is the combination of a range of observational technologies that has built Australia's reputation for astrophysics, and leverages access to other international projects, including space missions. Over the coming decade, Australia must continue its active engagement with both SKA and ELT, participating in the refinement of science cases, design and prototyping, with the intention of being at least 10% partners in both as they come to maturity.

This engagement offers great opportunities, not only for pure research, but also for the involvement of Australian industry at an early stage in developments. It is possible that the SKA will be built in Western Australia, offering yet more opportunities for diffusion of the investment in science into yet wider economic benefits. An ELT, by contrast, will be sited overseas; however, early engagement and commitment will maximize the opportunity for Australian industry to construct components of the instrument and participate in actual construction.

Australia's role in the international gravity wave observatory should also be supported through Australia's subscription to the ALIGO program. However, until gravity waves are detected they remain in the realm of experimental physics. Thus the priority attached to support for the AIGO facility and its upgrade should be primarily determined by the physics community it currently serves.

3.5.6 Addressing the Big Astronomical Questions

The "Big Questions" preface outlined the fundamental questions that will drive astronomical research around the globe in the next decade, and beyond. The following chart outlines how the various elements of the Astronomical Pyramid described above will permit Australian astronomers to successfully address these Big Questions.

The Big Questions	*Facilities*					
	University	National		International		
	All	Optical	Radio	8m	ELT	SKA
Dark energy & dark matter	✓	✓	✓	✓	✓	✓
Testing Einstein's			✓			✓
First stars Universe			✓		✓	✓
Galaxy Assembly & Evolution	✓	✓	✓	✓	✓	✓
Origin of Magnetism			✓			✓
Forming stars and planets	✓	✓	✓	✓	✓	✓
Planetary systems	✓	✓		✓		✓
Habitable systems					✓	

Creation of the elements	✓	✓		✓	✓	

Figure 3.2 The Mapping of the Science Questions onto the Proposed Infrastructure

3.5.7 Resourcing the plan

Indicative resource requirements to achieve this plan amount to approximately $50m of new money over the next five years, rising to $75m in the second half of the decadal planning period. Further reprioritization of up to $50m from existing operations into new programs would enable the Australia's top priorities to be achieved; minimum 10% participation in SKA and ELT, 20% access to 8m-class optical/infrared telescopes and the PILOT program.

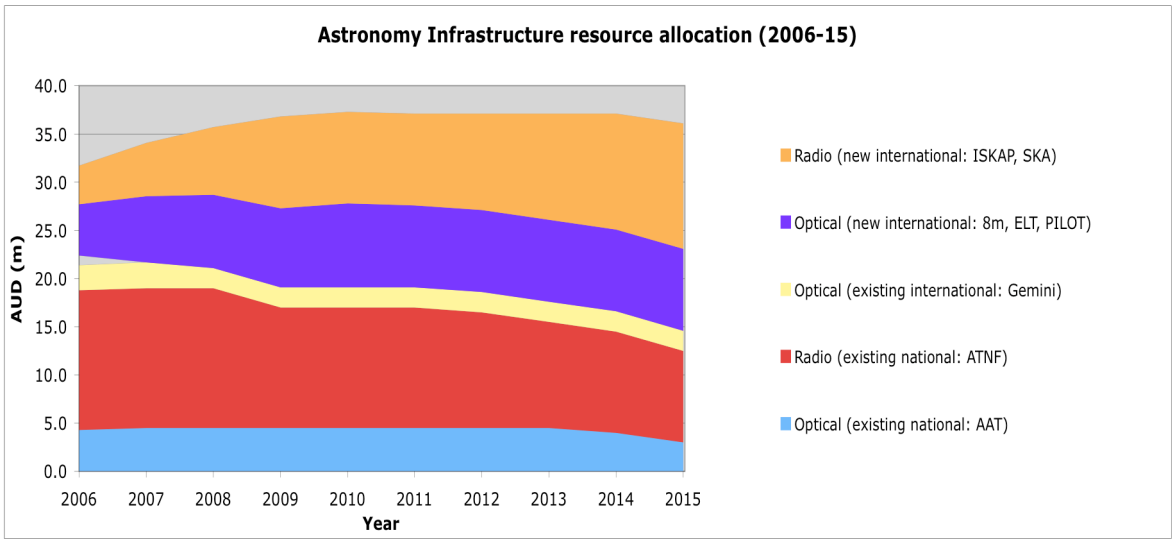

Figure 3.3 Proposed resource allocation for astronomy infrastructure 2006-15

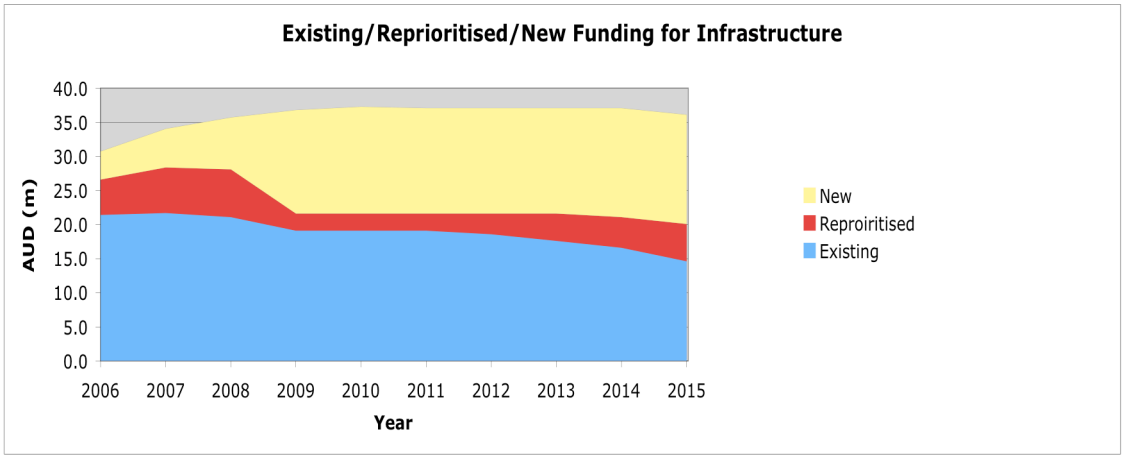

Figure 3.4 Distribution between existing, reprioritized and new investment in infrastructure

Further ongoing support at the level of approximately $5m per annum – with equivalent matching University resources – in the competitive grants line is required to support high priority University programs; potentially including those that leverage international collaboration (Auger, ALIGO) and those that support a broad national community (e.g. ANU's Siding Spring Observatory).

4. Australian Astronomy 2015

This plan lays out an ambitious and achievable roadmap for Australian astronomy over the coming decade. By following these strategies, appropriately resourced, it will have seen astronomers making contributions across the community in education, research, industry and society at large.

Astronomy programs will, by 2015, have expanded their training of PhD students – both through graduating more PhDs than 10 years previously, and by doubling the number of those PhDs teaching and working in industry. Australian astronomers will have been a catalyst in the enhancement and quality of science education at all levels across the country.

The size of the astronomical community will have expanded over 2005 levels. Australian astronomy will have maintained its position as the nation's leading scientific discipline as measured by the citation impact of our research results. And Australia will be participating in the leading international projects in which the nation has recognised astronomical strengths.

Australian astronomy has a proud record of outstanding achievement. We want these achievements to have continued over the decade, so that they can be a source of pride and benefit for all Australians.

Coda: A future retrospective

It is October 2015. Presidents and Prime Ministers from around the globe have travelled to Western Australia to take part in the ground-breaking ceremony for the mighty Square Kilometre Array – the largest radio telescope the world has ever seen. Already the Pathfinder facility for the SKA, which has been operating nearby for 4 years now, has detected glimmers of the light from the first stars formed in the early Universe. Once SKA goes into full operation in another five years, it will not only map the structure of the early Universe in unprecedented detail, but also listen for the ringing of space-time itself as pairs of black holes collide.

And at the end of next year many of the same world leaders will be meeting again in Chile, for the first light festivities of Australia's largest ever optical telescope, the international ELT. Built in collaboration with nations from around the world, its cricket-pitch-sized mirror will have the fine spatial resolution necessary to see the light from planets orbiting distant stars. While the telescope's enormous light collecting power will make possible the detection and analysis of the first stars formed after the Big Bang, telling us about the history of the fourteen billion years worth of Universe that their light has travelled through to get to us.

Meanwhile on the dry, cold highlands of the Australian Antarctic Territory, the world's first fully-cryogenic optical/infrared telescope, PILOT, is closing up at the end of its last six-month-long night of observing. Just a few years ago PILOT's detailed observations of Mars and Titan revealed weather patterns that have re-ignited the debate about life in the solar system. But the pace of development in astronomy is rapid, and it is now being closed down, in preparation for the construction of an even larger and more powerful 8m telescope which will be able to see the tiny wobbles produced as Earth-like planets orbit nearby stars.

All the data from these, and the rest of astronomy's ongoing explorations of the cosmos, is flowing into a vast storehouse of knowledge – the International Virtual Observatory. This treasure trove of information is used by schools and universities across the globe, and has been the engine powering an international explosion of interest in astronomy, as students and researchers alike use it better understand the formation and evolution of the universe, the seeds of life, and the fundamental nature of matter and energy.

Glossary

AAO	Anglo-Australian Observatory
AARNet	Australian Academic Research Network
AAT	Anglo-Australian Telescope (optical/infrared)
AEEMA	Australian Electrical and Electronic Manufacturers' Association
AIIA	Australian Information Industry Association
AIGO	Australian Interferometric Gravitational-Wave Observatory
ALIGO	Advanced Laser Interferometric Gravitational-Wave Observatory
ANU	Australian National University
ATNF	Australian Telescope National Facility (radio)
Auger	International Cosmic-Ray Observatory
CANGAROO	Collaboration between Australia and Nippon for a Gamma-Ray Observatory in the Outback
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ELT	Extremely Large Telescope (optical/infrared)
Gemini	Twin 8m-diameter optical/infrared telescopes
GSAOI	Gemini South Adaptive Optics Imager
GWFMOS	Gemini Wide Field Multi-object Spectrograph
LIEF	Linkage, Infrastructure and Equipment Fund
MNRF	Major National Research Facilities
NASA	National Aeronautics and Space Administration (US)
NIFS	Near-infrared Integral Field Spectrograph
OWL	Overwhelmingly Large Telescope (optical/infrared)
PILOT	Pathfinder for an International Large Optical Telescope (opt/ir)
SKA	Square Kilometre Array (radio)
SSO	Siding Spring Observatory
(x)NTD	(extended) New Technology Demonstrator (radio)