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Astronomy in Australia

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Australians have watched the sky for tens of thousands of years. The nineteenth century saw the foundation of government observatories in capital cities such as Sydney and Melbourne. While early twentieth-century astronomy focused largely on solar physics, the advent of radio astronomy at the end of the Second World War enabled Australia to take a leading role in the new science, with particular emphasis on low-frequency studies. Today, the radio quietness of its outback interior provides an excellent location for the Australian core of the Square Kilometre Array. Australian optical astronomy has flourished since the 1960s, with the 3.9-metre Anglo-Australian Telescope becoming the principal national facility in 1974. Access to ESO's facilities at the La Silla Paranal Observatory is warmly welcomed by all Australian astronomers.

It is no idle boast that Australia has the world's oldest continuing culture. Recent research at a rock shelter in Kakadu, near Jabiru in Australia's Northern Territory, used optically-stimulated luminescence to date human settlement there back to a staggering 65 000 years. Stone tools and buried ochre pigments suggest the inhabitants were both technologically and culturally adept, with observations of the sky likely being an important part of their daily rituals.

Australian Aboriginal people trace their cultural heritage back to the Dreamtime — an ancient era of creation, rich in legends linking human and animal life with the country in which they lived. Dreamtime stories differ from one Aboriginal nation to another, but are full of allusions to the sky, with the Sun, Moon, planets and stars all playing significant roles. The Milky Way is also important, with "negative constellations" being identified in its dust lanes. The most notable of these, which is common to many different Aboriginal peoples, is the Emu, whose head, neck and body are the Coalsack Nebula and the dust clouds of Circinus, Norma and Scorpius.

Conventional "join-the-dots" constellations also abound, but vary widely from one Aboriginal culture to another. Orion, for example, is seen as Njiru (the hunter) in the Central Desert Region, but the Yolngu people of Northern Australia see the constellation as a canoe, with three brothers sitting abreast in the centre (Orion's Belt) and a forbidden fish in the canoe represented by the Orion Nebula. Virtually all Dreamtime stories characterise the Moon as male and the Sun as female, with a tacit understanding that the covering of the Sun by the Moon during an eclipse represents the consummation of the relationship. Likewise, planets figure in Dreamtime astronomy, with Venus, for example, taking on a personage known as Barnumbir in Arnhem Land. Barnumbir is a woman held firmly on a rope extending from the eastern horizon (morning star) or western horizon (evening star), a neat explanation for the planet's limited excursions from the Sun.

Besides the creation myths, the stories told in Aboriginal astronomy served a practical purpose. The orientation of the Emu would indicate when it was time for the Central Desert people to begin collecting emu eggs. Likewise, the Boorong people in north-western Victoria used the constellation of Lyra to tell them when to gather malleefowl eggs. Dreamtime astronomy was also used to establish a moral framework among the younger members of the community, instilling values that had a demonstrable connection to their ancestor spirits in the sky.

Colonial astronomy

The arrival of the First Fleet in January 1788 brought up to 1500 British settlers to Port Jackson in Sydney. Over the next century, the effect of continuing settlement on the indigenous population was devastating. Meanwhile, the new colony flourished. The settlers included convicts, free settlers and military personnel, and its first noteworthy astronomical figure was William Dawes (1762–1836), a lieutenant in the Royal Marines. Besides his official position as engineer and surveyor to the new settlement, Dawes was also a botanist and a keen astronomer who built a small observatory at what is now called Dawes Point, close to the southern pylon of the Sydney Harbour Bridge. He is also notable as the first compiler of an Aboriginal language dictionary through his association with Petyegarang (Grey Kangaroo), a woman of the Eora Nation.

Of more lasting significance to astronomy is a piece of Australian-Scottish heritage centring around Sir Thomas Makdougall Brisbane (1773–1860), a conservation-minded soldier, statesman and scientist. Brisbane was the sixth governor of New South Wales (NSW), and an examination of his career prior to this suggests that astronomy was the principal driving force of his life.

The main reason for his keenness to become governor of NSW may have been to establish an observatory in Parramatta in 1822, which he wanted to become "the Greenwich of the Southern Hemisphere". The Parramatta Observatory has a precursor in Largs, Scotland (1808) that still exists, albeit in a highly dilapidated and unstable condition. This elegant stone building was lost to history until the early 1980s, standing on a hillside in the middle of what is now a cow pasture and almost overgrown by vegetation.

Brisbane's Parramatta Observatory (1822–1847) was essentially a copy of his Largs building, but in wood rather than stone, and equipped with positional instruments brought from Scotland. In turn, the Parramatta Observatory became the forerunner of the Sydney Observatory (1858), which inherited Parramatta's telescopes. The wooden observatory at Parramatta is long gone, but the stone supports for a later transit telescope remain in Parramatta Park. Brisbane himself left Australia in 1825 after visiting a new penal settlement near Moreton Bay, which now bears his name as the capital city of Queensland.

The first NSW Government Astronomer was William Scott, appointed in 1856, two years before the opening of the Sydney Observatory. Erected on the highest point of the new colony close to Dawes Point, the stylish sandstone

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Figure 1. Seen here at the time of its role in the Apollo lunar landings, the 64-metre Parkes Telescope is still a workhorse of Australian radio astronomy.

building is today dwarfed by the skyscrapers around it. Its principal function in the early years was to provide a timekeeping service for the community, complete with a time ball to allow mariners in the harbour to set their chronometers.

Astronomical research significantly advanced during the 35-year custodianship of the third Government Astronomer, Henry Chamberlain Russell, who was appointed in 1870. Highlights include the procurement of a 29-centimetre Schröder refractor in 1874, which is still operational; a major campaign to observe the 1874 transit of Venus; and the incorporation of the Sydney Observatory into the Astrographic Catalogue project in 1887. Russell also incorporated meteorology into the functions of the observatory.

Russell's efforts were criticised by a prominent amateur Australian astronomer, John Tebbutt (1834–1916), who is himself best known for discovering the spectacular comets of 1861 and 1881, and was honoured in 1914 by a visit from the Astronomer Royal Frank Watson Dyson. By then, Australia had attained nationhood in the wake of the Federation of 1901. Tebbutt's work was celebrated on the Australian $100 note from 1984 to 1996. The Sydney Observatory itself ceased astronomical research in 1982, reopening four years later as a public observatory under the auspices of Sydney's Museum of Applied Arts and Sciences.

The Great Melbourne Telescope

Another noteworthy observatory was built in the colony of Victoria as a direct result of wealth accumulated during the 1850s gold rush. June 1863 saw the foundation of a government-funded observatory in the capital city, Melbourne. The newfound riches of the Victorian government enabled the Royal Society to construct a large Southern Hemisphere reflector. The remarkable 1.2-metre Great Melbourne Telescope, then the world's largest working equatorial reflector, entered service in August 1869.

The Government Astronomer, Robert Ellery (1827–1908), expressed confidence in its capabilities as a premier research instrument. Sadly, this optimism was never fulfilled. The Great Melbourne's Cassegrain layout amplified the primary mirror's focal ratio to f/42, rendering the new technique of photography useless for all but the brightest objects. The mirror itself was made of speculum metal instead of with the newer technology of silver-on-glass. As a result, the mirror tarnished rapidly, requiring frequent risky re-polishing to restore its reflectivity. After many valiant efforts by Ellery, the Great Melbourne Telescope went into a long, slow decline and was eventually closed down in March 1944.

The telescope was then sold to the Commonwealth Solar Observatory at Mount Stromlo, on the outskirts of Canberra. Although it changed hands at scrap value (£500) it subsequently underwent a series of metamorphoses, culminating in the installation of a new 1.3-metre Pyrex mirror in 1959. The institution itself also metamorphosed into the Mount Stromlo Observatory of the Australian National University (ANU), which remains one of the nation's premier research centres.

In the early 1990s, the Great Melbourne Telescope, by then well over a century old, was reincarnated yet again to perform a specific scientific task — hunting for non-luminous objects in the galactic halo that might make up the mysterious “dark matter” known to permeate the Universe. This programme, called the MAssive Compact Halo Object (MACHO) experiment, was successful in effectively ruling out that possibility, and plans were well advanced in 2002 for the installation of a new camera that would be used in an ambitious survey for Kuiper belt objects — but then disaster struck.

On 18 January 2003, at the height of the bushfire season, a colossal firestorm in Canberra’s south-western suburbs claimed the lives of four people and left more than 500 families homeless. Mount Stromlo Observatory lost all its heritage buildings, including the domes of the Great Melbourne plus five other historically-significant telescopes. For six years, the twisted remains of the Great Melbourne Telescope lay rusting in the rains that followed the end of the once-in-a-hundred-year drought. In 2009, those remains were taken to the city of Melbourne to be restored and re-erected on the original site as a fully-operational public observing facility. That remarkable work is still ongoing.

The beginnings of Australian radio astronomy

Radio astronomy had its genesis in the work of Karl Guthe Jansky (1905–1950) of the Bell Telephone Laboratories in Holmdel, New Jersey. In 1932, he discovered radio interference at a wavelength of 14.5 metres coming from the Milky Way; this was largely ignored by the scientific community. Jansky’s antenna, a crude structure of wood and brass rotating on wheels purloined from a Model T Ford, was the first radio telescope.

It was followed in 1937 by the first steerable-dish type instrument, a 10-metre diameter reflecting radio telescope that was built not by Jansky but by another American, Grote Reber (1911–2002). Reber was the world’s sole radio astronomer for almost a decade, observing not just the Milky Way but also a range of radio sources. In 1954, he moved to Australia’s southernmost state, Tasmania, which was then largely radio quiet.

Radio astronomy in Australia had its origins in radar research carried out in the Second World War at what was known as the Radiophysics Laboratory, located at Sydney University. Following the end of hostilities, the renamed Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Radiophysics fragmented into a number of peacetime research groups; one such group was led by Joseph Pawsey (1908–1962) and was charged with investigating radio noise from extraterrestrial sources. At first, Pawsey’s group concentrated on solar radio emissions, near the South Head of Sydney Harbour. By 1947, this Dover Heights installation was being used to measure cosmic radio sources — most notably Cygnus A and the Crab Nebula in work led by John Bolton (1922–1993).

Other Australian astronomy pioneers include Wilbur Norman “Chris” Christiansen (1913–2007) and Bernard Mills (1920–2011), who both built radio array interferometers in the Sydney area. Mills adopted a cruciform configuration for his Mills Cross, and carried out all-sky surveys at 85.5 MHz (3.5 m). Christiansen adopted this configuration for the later “Chris Cross”, which was used in the mid-1950s for solar research.

The availability of war-time radar equipment precipitated the rapid development of radio astronomy. At first, the purveyors of this new science were engineers, who were regarded with deep suspicion by their optical counterparts. For example, Richard Woolley, then Director of the Commonwealth Observatory (today’s Mount Stromlo Observatory), was asked in 1947 where he thought radio astronomy would be in ten years’ time. “Forgotten,” was his acerbic reply.

Eventually, though, the two wavebands were seen as complementary, each providing different views of the Universe. Centres of excellence were established in Australia, the Netherlands and the United Kingdom, and instruments such as the 76-metre dish at Jodrell Bank (completed in 1957) and the 64-metre dish at Parkes in central western NSW (inaugurated in 1961; Figure 1) quickly became icons of the new science.

Australian radio astronomy had come of age by the time the Parkes Observatory was built, and the facility became well-known under the Directorship of John Bolton. It was instrumental in early studies of quasars and other extragalactic radio sources, pulsars, the Milky Way, and the interstellar medium. It also made history for its role in NASA’s Apollo program, as well as its ongoing contribution to the NASA Deep Space Network.

In its early days, Parkes was complemented by the Culgoora Radio Heliograph, built at Narrabri in north-western NSW under the leadership of Paul Wild (1923–2008). The instrument consisted of 96 dishes (each 13.7 metres in diameter), arranged around the circumference of a circle three kilometres in diameter. From 1967 to 1984, the Radio Heliograph operated first at 80 and then later at 160 MHz, imaging the Sun at these wavelengths once per second.

The Culgoora site was also home to a pioneering optical interferometer that borrowed more from radio astronomy technology than optical interferometry. This was the Narrabri Stellar Intensity Interferometer, the brainchild of radio astronomer Robert Hanbury Brown (1916–2002). It consisted of a pair of f/1.64 hexagonally-segmented collecting mirrors (6.7 metres in diameter) mounted on a circular track around which each mirror could move independently. The instrument was completed in 1963, and measured the angular diameters of 32 stars before it retired in 1974.

The Stellar Intensity Interferometer was operated by the University of Sydney. A more conventional optical interferometer was also built and opened in April 1991. This was the Sydney University Stellar Interferometer (SUSI), which was a Michelson interferometer with a variable baseline variable of 5–640 metres, fed by a dozen 0.2-metre siderostats operating in pairs. While SUSI achieved an excellent track record in high-resolution optical astronomy, it eventually closed in the face of competition from ESO’s Very Large Telescope Interferometer (VLTI) and other facilities.

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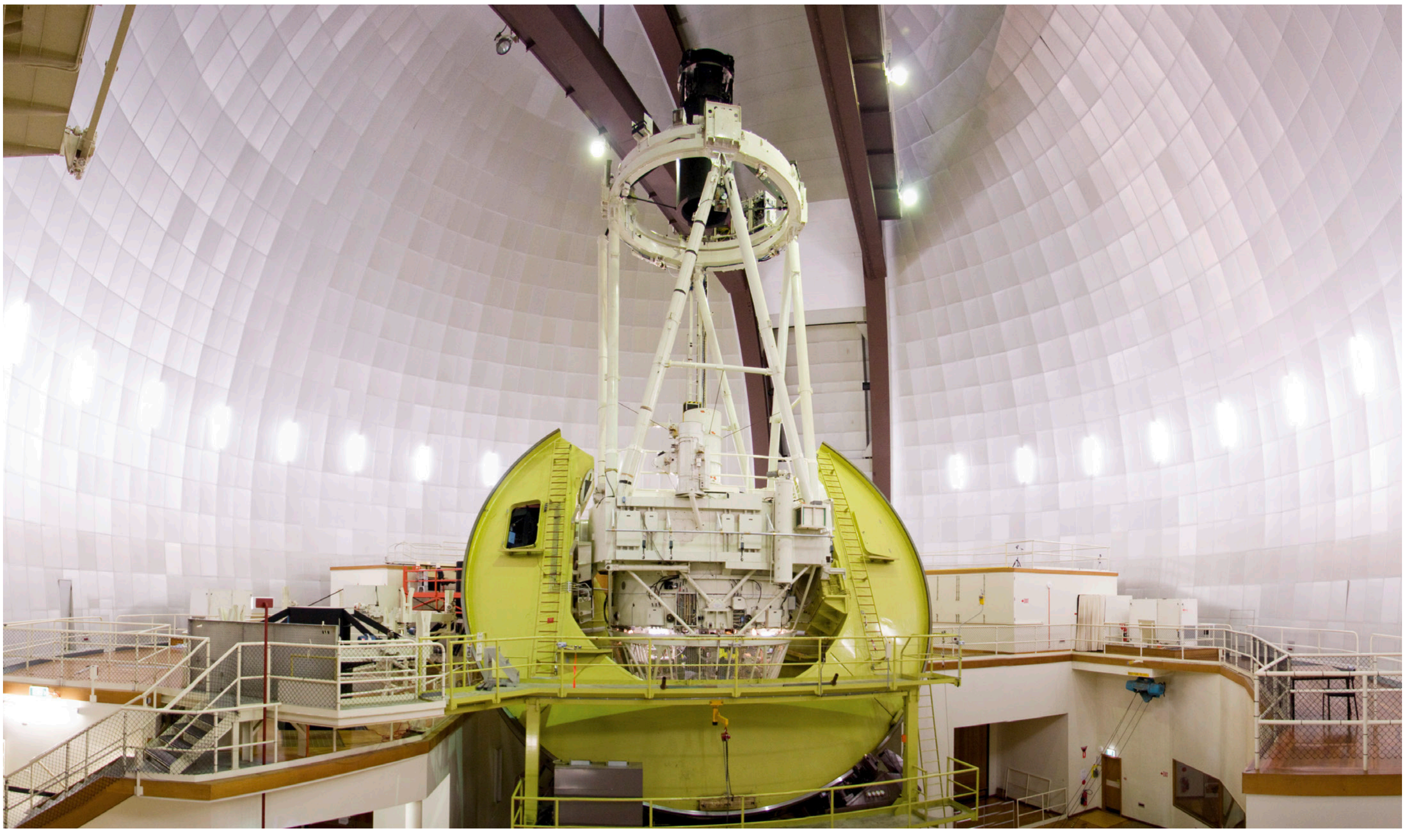

Figure 2. The 3.9-metre Anglo-Australian Telescope, opened in 1974, and became operational the following year.

Since 1988, Culgoora has been the location of CSIRO's Australia Telescope Compact Array, a group of six 22-metre radio dishes movable on a linear track, giving a maximum separation of six kilometres. The Compact Array is part of the Australia Telescope National Facility, which includes the 64-metre Parkes dish.

Siding Spring observatory

By 1960, the optical telescopes at Mount Stromlo Observatory were facing increasing light pollution from the encroaching suburbs of Canberra. The then-Director, Bart Bok (1906–1983), initiated the quest for a new dark sky site for the Australian National University's facilities, and selected Siding Spring Mountain. This 1200-metre high ridge in the Warrumbungle Range of north-western NSW was found to experience spectroscopic conditions for 65 % of the time, and photometric conditions for 35–50 % of the time, together with atmospheric turbulence as low as any other mountain site in Australia. The deciding factor in the selection was the small country town of Coonabarabran approximately 30 km away, which could provide infrastructure and accommodation for the supporting staff.

The first telescope was opened at Siding Spring in 1964, a 1-metre Boller and Chivens reflector quickly made famous by Bok and his wife, Priscilla Fairfield Bok, through their studies of the Milky Way. It was followed by two smaller ANU telescopes and, crucially, by infrastructure such as observer accommodation, power, water and a paved road to Coonabarabran.

The paucity of observing facilities for Australian and British optical astronomers led to the next major development. During the early 1960s British optical astronomers had access to a few small telescopes (up to 0.9 m), together with the 1.9-metre Radcliffe Telescope at Pretoria, South Africa, while their colleagues who worked at longer wavelengths had access to the impressive 76-metre dish at Jodrell Bank. Australian optical astronomers were similarly challenged, as their facilities at Siding Spring were dwarfed by the new Parkes Telescope.

When the British and Australian governments looked jointly at possible sites for a new 4-metre class telescope during the late 1960s, Siding Spring was considered to be the best location in Australia. This instrument eventually materialised as the 3.9-metre Anglo-Australian Telescope (AAT; Figure 2), which became operational in 1975. Observing time on the instrument was allocated equally between the two countries, an eminently successful arrangement.

The telescope itself was also extraordinarily successful from the beginning, partly as a result of its high level of computer control, the first for any instrument of this size. It was designed with versatility in mind, with a set of three interchangeable 4-tonne top-ends for the telescope providing a range of focal ratios from f/3.3 to f/36 at prime, Cassegrain and coudé focal stations. An auxiliary suite of more than a dozen instruments was built to take advantage of this and satisfy the wide-ranging scientific interests of Australian and British astronomers. The AAT was an early pioneer of electronic detectors, including the Image Photon Counting System (IPCS) developed at University College London by Alec Boksenberg.When used with a spectrograph, the IPCS rendered the AAT at least as powerful as any other telescope in the world, providing astronomers with a unique tool for investigating the detailed properties of every kind of celestial object.

Two other circumstances conspired to increase the AAT's potency as a discovery machine. Firstly, the southern sky was essentially unexplored by large telescopes. Even obvious targets such as the Galactic Centre and the Magellanic Clouds had been observed only at low elevations by northern-hemisphere instruments. Secondly, the British decided to construct a wide-field photographic survey instrument in 1970: the 1.2-metre UK Schmidt Telescope (UKST).

The UKST opened at Siding Spring on 17 August 1973. Its initial task was to photograph the whole of the southern sky not covered by its near-twin, which conducted a survey on Palomar Mountain (USA) during the 1950s; the UKST took the better part of a decade for this task. In June 1988, the symbiotic relationship between the two telescopes was formalised, when the UKST became part of the Anglo-Australian Observatory (AAO) instead of an outstation of the Royal Observatory, Edinburgh. In 2010, the AAO itself transformed into the Australian Astronomical Observatory, when the original bi-national agreement was terminated and funding was taken over by the Australian Government.

Siding Spring has continued to attract astronomical infrastructure (Figure 3), at least partly due to its dark skies and legislative protection against light pollution. The ANU's 2.3-metre Advanced Technology Telescope was inaugurated in 1988, and the privately-funded 2-metre Faulkes Telescope South (now the Las Cumbres Observatory 2-metre telescope) followed in 2004. The ANU's 1.3-metre SkyMapper telescope and the 1.6-metre Korean Microlensing Telescope are more recent additions. In January 2013, all Siding Spring's facilities were under threat from a devastating bushfire that started almost exactly a decade after the Mount Stromlo fire. In the event, the only casualty was the old observer accommodation, which has been replaced by a multi-purpose Lodge.

ANU

Figure 3. Siding Spring Observatory from the air, with the dome of the 3.9-metre Anglo-Australian Telescope in the centre, the 1.3-m ANU SkyMapper Telescope on the extreme left, and the 1.2-metre UK Schmidt Telescope and 2-metre Las Cumbres Observatory Telescope on the right.

Advanced radio instrumentation in Australia

A hallmark of Australian astronomy, both in universities and at national facilities, has been the development of innovative instrumentation. Radio astronomy leads the way in nationally-significant infrastructure. Scientists at CSIRO and elsewhere have built on the successes of the 20th century, leading international collaborations that are now developing major new facilities. The Murchison Widefield Array (MWA), which exploits Australia's expertise in low-frequency astronomy, is a joint project between approximately 15 institutions from Australia and abroad. Built between 2007 and 2012, the facility is located at the Murchison Radio-astronomy Observatory (MRO) at Boolardy in outback Western Australia. The radio quietness of this area is comparable to the pristine dark skies of Siding Spring, and the MWA's 128 phased dipole antennas give the telescope an extraordinary 30-degree field of view. Its scientific objectives include the detection of neutral hydrogen in the epoch of reionisation, together with heliospheric, ionospheric and interstellar medium research.

Boolardy is also home to CSIRO's Australian Square Kilometre Array Pathfinder (ASKAP; Figure 4), a radio telescope under construction since 2009. When completed, ASKAP will have 36 parabolic antennas, each 12 metres in diameter and equipped with advanced phased array feeds with a 6-degree field of view. ASKAP is a survey telescope, with cosmology and early galaxy evolution among its principal scientific objectives. The 12 antennae currently operating generate 5.2 terabytes of data per second — approximately 15 % of the entire internet's data rate. During initial commissioning in January 2017, several fast radio bursts were detected from an as yet unknown source. ASKAP is likely to detect a fast radio burst every few days once it is fully operational, with good prospects for unravelling the nature of these enigmatic phenomena.

As its name suggests, ASKAP demonstrates the technology of the Square Kilometre Array itself, a multi-national facility

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Figure 4. 12-metre antennae of the Australian Square Kilometre Array Pathfinder in Western Australia.

that will be the world's largest telescope when completed in the late 2020s. The SKA will consist of widely-dispersed radio arrays in Southern Africa, New Zealand and Australia; due to its radio quietness, the MRO will be one of its core sites. The primary science objectives are centred on fundamental cosmology and extragalactic astronomy, with an emphasis on black holes, large-scale structure, and the Universe's "Dark Ages".

Astrobiology will also feature among SKA's scientific programmes, with prebiotic chemistry, protoplanetary discs, and the search for extraterrestrial intelligence being of interest. The Parkes Observatory is already working on pathfinders of the latter area of research; 25 % of its observing time is currently devoted to the "Breakthrough Listen" initiative.

Optical instrumentation and the AAO

Advanced instrumentation is also flourishing in Australian optical astronomy. The ANU's Research School of Astronomy and Astrophysics (RSAA) at Mount Stromlo, for example, has a fine track record of developing hybrid imaging detectors. It has completed two instruments for the 8-metre telescopes of the Gemini Observatory: the Near-infrared Integral-Field Spectrometer (NIFS) and Gemini South Adaptive Optics Imager (GSAOI). The Advanced Instrumentation Technology Centre (AITC) at Mount Stromlo also provides excellent facilities for instrumentation scientists and engineers at RSAA.

The AAO's scientists and engineers have honed their skills developing novel instruments for use with the AAT. In 1979, observations at infrared wavelengths with the Infrared Photometer-Spectrometer (IRPS) enabled the AAT to see through dust clouds and study the earliest stages of star formation. The infrared instrumentation that followed, the InfraRed Imaging Spectrometer (IRIS) and later IRIS2, also produced spectacular results, including imaging the 1994 impacts of Comet Shoemaker-Levy 9 fragments with Jupiter, as well as detailed observations of galactic and extragalactic targets.

However, it was the early use of optical fibres that set the AAO on its current course. While multi-fibre spectroscopy was not invented at the AAO, it was transformed from an interesting novelty to a highly productive technique during the early 1980s at the AAT and UKST. After pilot surveys, the AAO unveiled 2dF (Two Degree Field) in the mid-1990s, which allowed the spectra of 400 objects to be obtained simultaneously using robotically-positioned fibres.

The 2dF Galaxy Redshift Survey measured 221 000 galaxies and quickly became one of the most productive projects at the AAO in terms of both publications and citations. It helped establish the "missing link" between temperature fluctuations in the cosmic microwave background radiation and today's distribution of galaxies. Building on this success, the AAO produced a series of stationary spectrographs to be fed by 2dF. This included both the intermediate-dispersion AAOmega instrument in 2006, which remains one of the world's most powerful spectroscopic survey instruments, and HERMES in 2014, a high-dispersion spectrograph designed for galactic archaeology.

In 2001, the UKST also began a new role as a dedicated spectroscopic survey telescope using a robotic instrument called 6dF, originally a prototype for the OzPos fibre positioner delivered to Unit Telescope 2 of the VLT in 2003. Its first major project was the 6-degree Field Galaxy Survey (6dFGS). UKST also conducted the RAdial Velocity Experiment (RAVE) survey, a multi-national project that measured the radial velocities and physical parameters of half a million stars. Two new UKST surveys, Taipan and FunnelWeb, will use a novel fibre positioner in which each of the 300 fibres is positioned by its own micro-robot rather than a pick-place machine (Figure 5). This "Starbugs" technology was developed by the AAO as a demonstrator for the proposed Many Instrument Fiber System (MANIFEST), on the 25-metre Giant Magellan Telescope.

Another recent innovative instrument on the AAT is the Sydney-AAO Multi-object Integral field spectrograph (SAMI), which deploys 13 integral field units (IFUs) over a one-degree field of view and is being used to conduct the first major IFU survey of nearby galaxies. AAT instruments currently in development include HECTOR (a more powerful version of SAMI) and Veloce, a stabilised high-resolution (R ~ 80 000) echelle spectrograph for stellar spectroscopy.

Other AAO instrument projects include the Australian–European Southern Observatory Positioner (AESOP), a 2400-fibre tilting-spine positioner for ESO's

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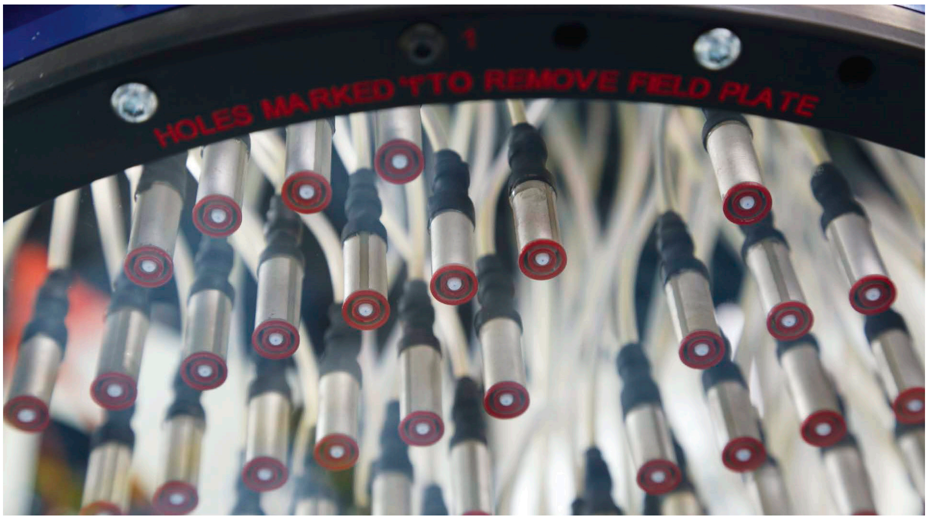

Figure 5. "StarBugs" on the glass focal plate of the 1.2-metre UK Schmidt Telescope. Each Bug is eight millimetres in diameter and contains an autonomous positioning robot, three metrology fibres and a science-fibre payload.

4-metre Visible and Infrared Survey Telescope for Astronomy (VISTA), and the Gemini High-Resolution Optical SpecTrograph (GHOST) for the Gemini South telescope in collaboration with the Herzberg Institute for Astrophysics in Canada and the Australian National University. More fundamental instrumentation research is also being carried out, particularly in astrophotonics. In collaboration with the University of Sydney, Macquarie University and the University of Western Australia, the AAO has tested OH-suppression devices based on fibre Bragg gratings, as well as slab-waveguide photonic spectrographs and photonic-comb calibration cells. The work on these devices is expected to radically change the way in which astronomical instruments are built, plus add entirely new capabilities.

Following the recent launch of Australia's ten-year strategic partnership with ESO, the AAO will split into two separate entities as of 1 July 2018. Operation of the AAT and UKST will be passed over to a consortium of Australian universities led by the ANU, which owns the Siding Spring site. The AAO's instrumentation and astronomy groups will be handed over to the research sector. The exact details of these new arrangements are yet to be defined; however the AAO brand name will be retained to ensure the pedigree of future astronomical instrumentation is not in doubt. A new era of instrument-building awaits the engineers and scientists of AAO, and it is expected that ESO will be one of its principal benefactors.

As well as the high-profile work outlined here, there are numerous university research endeavours in a range of fields including cosmic ray astronomy, gravitational wave astronomy, and space physics. Major facilities can also eclipse important activities in smaller observatories; for example, the research conducted by the University of Southern Queensland's Mount Kent Observatory and public outreach at the former Government Observatory in Perth, Western Australia.

Australia and ESO

Australian astronomers have long coveted the idea of an affiliation with ESO. They warmly applauded on 11 July 2017 at an event at the Astronomical Society of Australia's Annual Scientific Meeting in Canberra, when Arthur Sinodinos (Minister for Industry, Innovation and Science) and Tim de Zeeuw (ESO Director General) exchanged signatures to inaugurate the strategic partnership.

What exactly does this arrangement involve? While current fiscal realities prohibit full Australian membership of ESO, the ten-year strategic partnership that Australia formally entered on 11 July 2017 provides long-term access to the facilities at La Silla and Paranal. Access to the four 8.2-metre Unit Telescopes of ESO's VLT at Paranal is an important prize for Australian astronomers, whose critical need for time on telescopes in this class has been highlighted in successive Decadal Plans for Australian Astronomy, including the current one (2016–2025). Short-term financial arrangements with other 8-metre class facilities provide little opportunity to contribute to the design and procurement of advanced instrumentation for the telescopes, an area in which Australia has particular expertise. The new partnership with ESO explicitly aims to capitalise on that know-how, with promised benefits not only for technologically-adept institutions such as the AAO, but for partners in Australian universities and industry.

However, technology is only one of the reasons ESO welcomes Australian involvement. Another — also highlighted in successive Decadal Plans — is the high-impact science carried out by Australian astronomers. It has often been stated that Australian astronomical research "punches well above its weight", and Australia's scientific clout can only be increased by access to ESO's facilities. Australian astronomers became eligible in Period 101 to compete for time alongside astronomers based in ESO Member States, and no fewer than 55 Australian-led proposals were submitted.

Excluded from the new partnership is the Atacama Large Millimeter/submillimeter Array (ALMA), since access to this 5100-metre high submillimetre facility has lower priority for Australian astronomers than access to 8-metre class optical telescopes. Likewise the Extremely Large Telescope is excluded due to Australia's established participation in the proposed 25-metre Giant Magellan Telescope, also in northern Chile. Eventually, Australia will have the opportunity to enter into full ESO membership with access to ALMA and the ELT. While it is difficult to chart the financial landscape over the course of the current decade-long partnership, there is optimism that this is a real possibility.