1 Siding Spring Observatory is dominated by the dome of the 3.9 m Anglo-Australian Telescope (centre). On the extreme left is the 1.3 m ANU SkyMapper Telescope, while the 1.2 m UK Schmidt Telescope and Las Cumbres Observatory 2 m Telescope are on the right. (ANU)

A new era for Australian astronomy

It's all change for the Australian Astronomical Observatory – **Fred Watson** and **Jane Urquhart** explain what is happening to this astronomical powerhouse.

It's hard to think of a time when the landscape of Australian astronomy was changing as rapidly as it is at present. Perhaps during the pioneering days of radio astronomy following the second world war? Or in those heady days, three decades later, when optical astronomy was revitalized by the Anglo-Australian Telescope (figure 1)? Today, radio astronomy in Australia maintains a steady-as-she-goes approach, with innovative new facilities paving the way for the Square Kilometre Array in the 2020s. But the optical community is undergoing epochal transformation – bringing both opportunities and challenges.

At the heart of the changes is infrastructure – which, for astronomers, of course, means telescopes and instrumentation. Being a well-organized cohort, Australian astronomers carefully review all aspects of their science on a decadal basis, incorporating the results into a formal planning document. Thus they can stocktake their inventory of facilities and spell out their aspirations with cogent scientific arguments to support them. And successive decadal plans for Australian astronomy – including the current one, *Australia in the Era of Global Astronomy, 2016–2025* (Australian Academy of Science 2015) – have highlighted the need for significant amounts of time on optical telescopes in the 8 m class.

"The ability to use the telescopes of ESO's VLT is an important prize for Australian astronomers"

Looking to Europe

In recent years, such access has been granted by relatively short-term financial agreements with overseas institutions. While they have been scientifically productive, these arrangements have provided little opportunity to influence the design and procurement of advanced instrumentation for the telescopes, an area in which Australia has particular expertise. So it is no secret that Australian astronomers have long coveted the idea of the nation being affiliated with ESO, the European Southern Observatory.

Of course, ESO membership involves significant cost, which demands high-level government support. A near-success two decades or so ago fell victim to budget pressures in the run-up to the 1996 federal election, relegating the issue to a fond hope in the bosoms of optical astronomers in Australia and Europe. But recently, with almost breathtaking swiftness, there has been a shift in the fortunes of those

2 An historic day for Australian astronomy: the minister for industry, innovation and science Arthur Sinodinos, and the director general of ESO Tim de Zeeuw, sign the partnership agreement between Australia and ESO in July 2017. (DIIS)

3 A sunset portrait of the four 8.2 m Unit Telescopes of ESO's VLT at Paranal. (J C Muñoz-Mateos)

ambitions. Rumours of behind-the-scenes negotiation gave way to a blaze of publicity at the Astronomical Society of Australia's 2017 Annual Scientific Meeting in Canberra. There, on 11 July, a 10-year strategic partnership was inaugurated by senator the Hon. Arthur Sinodinos, then Commonwealth minister for industry, innovation and science, and Tim de Zeeuw, then ESO director general (figure 2).

Although this arrangement does not constitute full Australian membership of ESO (which current fiscal realities prohibit), it does provide long-term access to the world's most comprehensive suite of optical astronomy facilities at La Silla and Cerro Paranal in northern Chile. The ability to use the four 8.2 m Unit Telescopes of ESO's VLT at Paranal (figure 3) is an important prize for Australian astronomers, fulfilling the critical requirement for this class of instrument. The new deal also explicitly aims to capitalize on Australian know-how in instrumentation, with promised benefits for domestic universities and industry.

Technology is only one of the reasons ESO is keen on Australian involvement, however. Successive decadal plans have highlighted the high-impact science carried out by Australian astronomers, whose contribution can only be enhanced by the new facilities now becoming accessible. These facilities were warmly embraced by Australian astronomers during the first round of ESO telescope time applications available to them. This was for period 101, whose closing date was a mere two-and-a-half months after the partnership was signed into existence. No fewer than 55 Australian-led proposals were submitted by 160 astronomers from 16 Australian institutions – 6% of all the proposals – reflecting, perhaps, a long pent-up demand on the part of the Australian community.

Excluded from the new partnership is ESO's Atacama Large Millimetre Array (ALMA) at the Llano de Chajnantor site near San Pedro de Atacama. Access to this 5100 m altitude submillimetre facility has lower priority for Australian astronomers than use of the 8 m class optical telescopes. Likewise, ESO's 39.3 m Extremely Large Telescope (ELT), currently under construction at Cerro Armazones (near Paranal), is excluded. Until the conclusion of the strategic partnership in 2027, however, Australia will have the opportunity to enter into full membership of ESO, with access to both ALMA and ELT. While it is difficult to chart the financial landscape that will then prevail, there is optimism that this will be a real possibility.

The other side of the coin

The government's initiative in forging the partnership with ESO has been widely praised within the Australian astronomical community. The concomitant change, however – which, at the time of writing, is in the final stages of formulation – heralds the biggest makeover in the 44-year history of the Australian Astronomical Observatory (AAO).

Until 2010, AAO was the Anglo-Australian Observatory, a UK–Australian institution with joint funding that was frequently held up as an exemplary international collaboration. Following the UK's withdrawal from the agreement in 2010, the observatory became a division of the Australian government's science department, which is today the Department of Industry, Innovation and Science (DIIS). That metamorphosis left the key functions of the old AAO intact; namely, operation of the 3.9 m Anglo-Australian Telescope (AAT) and 1.2 m UK Schmidt Telescope (UKST) at Siding Spring Observatory near Coonabarabran, and the observatory's technology and facilities base in Sydney. Some readers will recall with affection the AAO's somewhat ramshackle Sydney offices in the leafy northern suburb of Epping. In 2012, however, a move was made to new purpose-built premises in North Ryde – no less leafy by virtue of nearby parkland (and the Northern Suburbs Crematorium), but lacking the soul of the Epping lab.

The advent of Australia's partnership with ESO draws a line under this chapter in the AAO's history, and the old operating model will come to an end on 30 June 2018. What will replace it is a move from the government to the research sector, with the Coonabarabran and Sydney operations falling under two different university consortia. Once again, it is fiscal reality that dictates the need for this transformation. Without it, the observatory's finances would have cascaded over a precipitous funding cliff in 2020. With it, the requirements of the decadal plan in maintaining the key functions of the AAO until at least the mid-2020s can be met.

The new model for the AAO's facilities places the operation of the AAT under the management of Astronomy Australia Ltd (AAL), a not-for-profit company whose members are Australian universities and research organizations with significant astronomical research capabilities. Founded in 2007 to manage collaborative research infrastructure grants in astronomy, AAL remains an advocate for Australian astronomy facilities. From 1 July 2018, the Commonwealth will lease the premises exclusively to the Australian National University (ANU), acting on behalf of a consortium of 13 fee-paying Australian universities. The ANU already owns and operates Siding Spring Observatory on which the AAT is located, and has several of its own staff there as well as staff from

4 The 3.9 m Anglo-Australian Telescope, opened in 1974. (A López-Sánchez)

other institutions with facilities on the site. The AAT Consortium agreement will cover the operation of the telescope for seven years; funds for the first four are already committed. While the telescope will continue to be the property of DIIS, its governance will be through a new AAT Council, whose membership will be drawn from the AAT Consortium and AAL. The majority of its staff will become ANU personnel.

The allocation of time on the AAT (figure 4) will continue more or less as at present, with an independent panel determining the programmes to be supported in each semester. The telescope will continue to be a national facility, available for cost-free use by astronomers at any Australian institution. A new category of paid time for non-Australian proposals, or proposals from Australian teams wishing to guarantee access, will also be formalized. (Astronomers interested in AAT paid time should contact AAL for more information: info@astronomyaustralia.org.au.) Enthusiasm for observations using the AAT with its outstanding suite of instruments has not waned throughout the transition process: applications for time in semester 18B (Aug 2018 – Jan 2019) reflected the normal oversubscription rate of two to three times the available nights.

"Indeed, business as usual could soon be bigger and better than ever"

New surveys for UKST

The situation for the UKST is rather different. Despite being operated by AAO since 1988, it has been owned by the ANU since the transition of 2010. As described later in this article, two new large-scale surveys (Taipan and FunnelWeb) will take up all available time on the telescope.

So much for the telescopes – what of the AAO's facilities in Sydney? Once again, the importance of the observatory's world-class instrumentation programme is highlighted in the decadal plan, and it will continue into the new era. Towards the end of 2017, several Australian institutions responded to a DIIS invitation for expressions of interest to host the AAO's science and technology groups. The successful bid came from a consortium led by Macquarie University and including the ANU and the University of Sydney, with funding primarily through AAL in partnership with the universities. All three of the universities involved have a history of innovative instrumentation research, frequently in collaboration with AAO.

At the time of writing, negotiations are still proceeding on details of the transfer to Macquarie University. In terms of the physical location of the AAO's Sydney group, it is likely that the North Ryde premises will be retained until new purpose-built accommodation is constructed on the Macquarie campus, some 4 km away. But it is also expected that the unity of the group will be retained within Macquarie University in order to preserve the internationally known AAO brand-name.

The transition of a government-funded institution like AAO is a complex and often emotional process. In AAO's case, it involves a revision of the Act of Parliament that brought the Australian Astronomical Observatory into being in 2010, as well as all the complex transition procedures for staff and assets. And the bottom line is that the university consortia that will now operate the two residual components of AAO must do so with funding that is significantly less than before. While every effort is being made to minimize the losses of staff in the transition, there are clearly significant risks to jobs and wellbeing. Uncertainty is the principal enemy of a smooth transfer, and a hard-working AAO Transition Team has been liaising throughout with stakeholders, including staff, the Science and Commercialisation Policy and the Corporate Divisions of DIIS and the principal universities. How successful this has been will not truly be known until the dust settles, but there are encouraging signs that things will return to "business as usual" soon after the transition. Indeed, with the instrumentation group becoming part of a truly national capability, business as usual could soon be bigger and better than ever.

An AAO retrospective

The history of the AAO, from its inception to its incorporation as an all-Australian institution in 2010, has already been covered in these pages (Watson & Colless 2010). Serious fans of the AAO are also encouraged to seek out the details of its origins in Gascoigne *et al.* (1990), and the highly personal account by Hoyle (1982). From the moment HRH Prince Charles arrived to "declare this aperture open" on 16 October 1974, the AAT's early history was unashamedly triumphal, with the pioneering colour imagery of David Malin taking the telescope firmly into the popular media, and early electronic detectors like the Image Photon Counting System reaping an enviable harvest of scientific discovery. Perhaps it is not too immodest to suggest that the observatory's final eight years have been equally successful, despite its observational facilities slipping inexorably down the world's ranking of large telescopes. As we shall see, however, size isn't everything.

Hot on the heels of the 2010 transition came the proceedings of an unusual conference that mixed nostalgia with history and hard science (Cannon & Malin 2011). The volume is littered with astronomical household names, including the Anglo-Australian Observatory's five directors (Joe Wampler 1974–76, Don Morton 1976–86, Russell Cannon 1986–96, Brian Boyle 1996–2003 and Matthew Colless 2004–12). It was perhaps fitting that Colless, as AAO's first Australian-born director, should steer the observatory through the transition to all-Australian status. He resigned in 2012 to take up his present position as director of ANU's Research School of Astronomy and Astrophysics – which, of course, operates Siding Spring Observatory.

It was during the interim directorship of Andrew Hopkins, early in 2013, that Siding Spring faced its most serious challenge. The Wambelong bushfire began in the heart of the adjacent Warrumbungle National Park and, fanned by hot January winds, quickly enveloped the mountaintop before bearing down on the nearby town of Coonabarabran. Before reaching Coona's outskirts, it abruptly changed direction, sparing the town but remaining dangerous for another week (figure 5). In the event, 55 000 hectares of national park and bushland were destroyed, along with more than 50 homes, fortunately without loss of life or serious injury. All the observatory's telescopes survived, albeit with some smoke and ash damage, but the astronomers' lodge was burned to the ground. It was in June 2017 that the ANU formally opened a new purpose-built lodge – but not before the building had been thoroughly tested by a large production team from the *Stargazing Live* TV programme. The AAT and some of its staff featured prominently in episodes broadcast by both the BBC and the Australian Broadcasting Corporation, continuing a long tradition of effective science outreach at the AAO (figure 6).

A further consequence of the Wambelong fire was the early introduction of remote observing on the AAT, prompted by lengthy restrictions in accessing the site. This began in an improvised observing suite at North Ryde and is now the preferred method of observing for about half of the AAT's users, with dedicated observing facilities available at several other Australian institutions as well as North Ryde. It is expected that within the next year, the UKST will also be operable remotely.

By the end of 2013, AAO's penultimate director was in post. Warrick Couch had been a chair of the AAT Board and, as director, negotiated the organization through the maze of regulation associated with its status as a division of a government department. Following Couch's resignation for personal reasons in December 2017, Jane Urquhart of DIIS took over AAO's helm for its final six months.

5 Siding Spring's worst day. With 50 m flames leaping up the southern flank of the mountain, the AAT and UKST (right) disappear into the smoke on 13 January 2013. All the telescopes survived. (R Paterson)

6 Famous faces under the Anglo-Australian Telescope. Brian Cox and Dara Ó Briain host BBC TV's *Stargazing Live* in March 2017. The ABC will repeat the show this year. (Á López-Sánchez)

Instruments and surveys

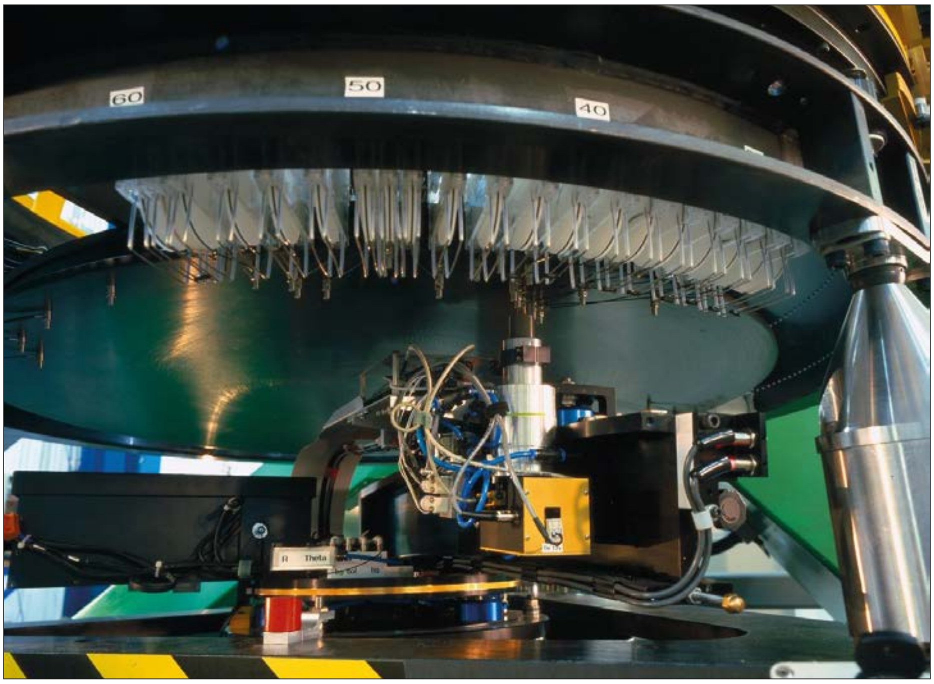
From the beginning, the AAO's Sydney-based scientists and engineers showed themselves to be adept at building novel instruments for use with the AAT. It was the early use of optical fibres, however, that set the observatory on its current course. While multi-fibre spectroscopy was not invented by the AAO, it was transformed from an interesting novelty into a highly productive technique at both the AAT and the UKST during the early 1980s. Pilot spectroscopic surveys on both telescopes demonstrated its potential and, in the mid-1990s, the AAO unveiled 2dF (for 2-degree Field) on the AAT. This ground-breaking instrument allowed the spectra of 400 objects to be obtained simultaneously using fibres positioned robotically in a field of view that was unprecedented on a 4 m class telescope.

2dF's first task was a three-dimensional survey of the distribution of galaxies within some 750 Mpc to provide a detailed cross-section of the universe. That project – the 2dF Galaxy Redshift Survey – measured 221 000 galaxies and was completed in 2002, quickly becoming one of the richest sources of AAO scientific papers to date. In 2005, it was used to find the "missing link" between the temperature fluctuations in the cosmic microwave background radiation and today's distribution of galaxies.

"AAOmega is still one of the world's most powerful spectroscopic survey instruments"

Building on this achievement, the AAO constructed a succession of room-sized spectrographs to be fed remotely by 2dF. In 2006, the intermediate-dispersion AAOmega became the telescope's workhorse for both galactic and extragalactic astronomy, and is still one of the world's most powerful spectroscopic survey instruments. It was followed in 2014 by HERMES, a high-dispersion spectrograph that was especially designed for galactic archaeology using detailed observations of very large numbers of individual stars. The current Galactic Archaeology with HERMES (GALAH) project has already

7 The definitive portrait of the UKST in the 6dF era, with the robot room on the left and the spectrograph enclosure on the right. The screen is for calibration exposures, not midnight movies. (B Wrigley)



8 AAO gets its own back. The OzPoz fibre positioner was built by the AAO for the VLT's FLAMES multi-object spectrograph. This early example of Australian equipment on overseas facilities is likely to be repeated under the new strategic partnership. (ESO)

netted the spectra of half a million stars. Another recent innovative instrument is the Sydney-AAO Multi-Object Integral field spectrograph, SAMI, which deploys 13 integral field units (IFUs) over a 1° field of view and is being used to conduct the first major IFU survey of nearby galaxies. Other AAT instruments currently in development include HECTOR (a considerably more powerful version of SAMI) and Veloce, a stabilized high-resolution ($R \sim 80\,000$) echelle spectrograph with precision wavelength calibration for stellar spectroscopy.

The 6dF on the UKST

Not to be outdone by its larger sibling, the UKST (figure 7) began a new role as a dedicated spectroscopic survey telescope in 2001 using a robotic instrument called 6dF, built as a prototype for the OzPoz fibre positioner (figure 8) delivered to UT2 of the VLT in 2003. Its first major project was the 6dF Galaxy Survey (6dFGS), measuring the redshifts of 150 000 galaxies, and peculiar motions for a substantial subset. The 6dFGS was finished in 2005 and the telescope went on to carry out the RAVE survey (for RAdial Velocity Experiment), a multinational project to measure the radial velocities and physical parameters of half a million stars. RAVE was completed in 2013, and its scientific legacy is still being exploited. But another key aspect of RAVE was that it pioneered a new mode of operation for the UKST, in which funding was provided by external contributions and was thus cost-neutral for the AAO. Eventually, perhaps, the AAT itself will be run on these lines for large-scale surveys.

This funding model is now being used in two new UKST surveys. They are Taipan (two million galaxies with $r < 17.5$ for cosmological and extragalactic studies, complementing a major project on ASKAP – the Australian Square Kilometre Array Pathfinder) and FunnelWeb (three million stars to generate the "Henry Draper Catalogue of the 21st century", with synergies relating to TESS and Gaia). Both are externally funded and use a novel fibre-positioner recently commissioned on the newly refurbished UKST (figure 9). Each fibre is now positioned by its own micro-robot, rather than with a pick-place machine like 2dF. All the fibres can be moved simultaneously, reducing reconfiguration time to a few minutes and avoiding the calibration overheads introduced by slit exchangers. This Starbugs technology has been developed by AAO as a demonstrator for MANIFEST, the proposed Many Instrument Fibre System on the 24.5 m Giant Magellan Telescope. In the present setup, 150 autonomous fibres patrol the 6° field of the UKST, but funding has been secured to increase that to 300 fibres.

Data Central

Not quite an instrumentation project, but vitally important for archiving and disseminating survey data, is AAO's Data Central. This new project, designed specifically to meet the needs of the Australian astronomical community, was funded by DIIS to provide a large-scale data archive capable of being scalable and extensible, as well as able to ingest and cross-match heterogeneous data. Launched in August 2017 with three sample datasets, Data Central is rapidly growing, and can be accessed at http://datacentral.aao.gov.au.

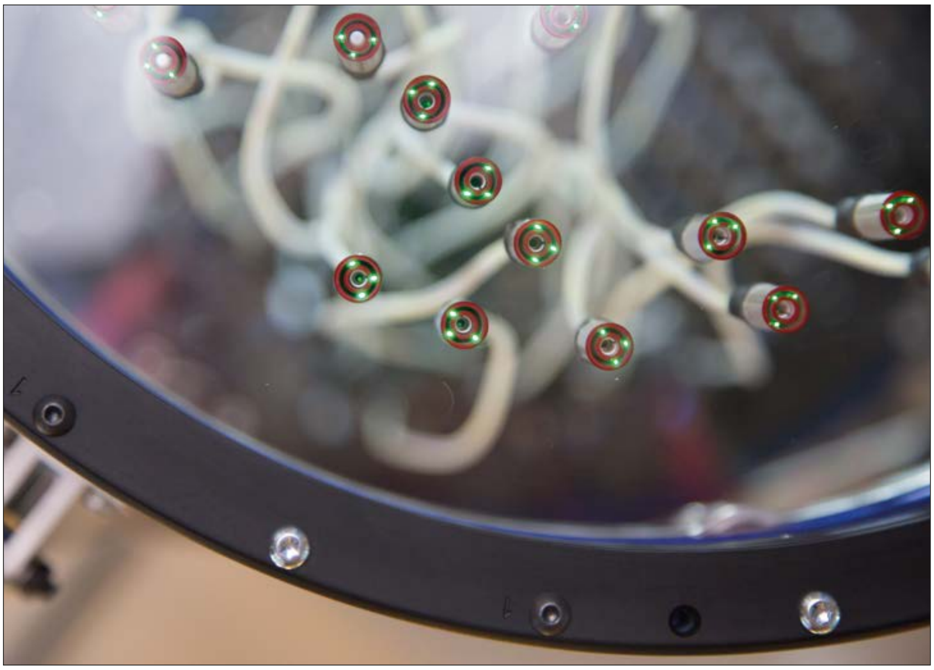
Other current AAO instrument projects include AESOP, a 2400-fibre tilting-spine positioner for ESO's 4 m VISTA telescope, and the Gemini High-Resolution Optical SpecTrograph (GHOST), which has been developed for the Gemini South telescope in a collaboration between AAO, the Herzberg Institute for Astrophysics in Canada, and the ANU. More fundamental instrumentation research is also carried out, particularly in astrophotonics. In collaboration with scientists at the University of Sydney, Macquarie University and the University of Western Australia, AAO has tested OH-suppression devices based on fibre Bragg gratings, and experimented with waveguide photonic spectrographs, ring resonators and photonic-comb calibration cells. These devices, or their successors, are expected to radically change the way in which astronomical instruments are built, and add wholly new capabilities.

Plus ça change…

One of the key ingredients for the success of the AAO over the years has been the relationship between the two ends of the organization. Yes, there has always been banter between them (typically "Coona has broken it again" vs "As usual, Epping has sent us a half-finished job"), but their mutual reliance and trust has delivered many a fine instrument at the cutting edge of astronomical technology. From 1 July, the telescope staff and the instrument builders will belong to separate organizations, and the connection between them will not be automatic. However, all parties are well aware of this requirement, and steps are being taken to preserve it.

Less likely to survive is the AAO's student fellowship programme. For many years now, the AAO has invited astronomy undergraduates to apply for 12-week placements during the long vacation. Because AAO was originally a bi-national institution that straddled the equator, that meant two student intakes for the northern and southern summer vacations, a tradition that continued in the all-Australian era. Competition for places was intense, but students always benefited from the experience, with many going on to become professional astronomers or instrument scientists. In fact, one former student became director of AAO itself. The programme continued the tradition of mentorship established in the early years of the AAO, when it was known as a "finishing school" for young astronomers. Because both halves of the former AAO will now be housed in universities, it seems probable that the December 2017 intake of AAO students will be the last in the current series. However, for the same reason, there will be many new opportunities for student vacation scholarships and full-scale student projects at both undergraduate and graduate level.

Beside its staff, its instrumentation programme and the efficiency with which its telescopes are operated, there has been one other major ingredient to AAO's success: its environment. Yes, Siding Spring's record of clear weather is not brilliant (typically 67%) and neither, by today's standards, is its level of atmospheric turbulence (median seeing 1.5 arcsec). But what it can offer is a night sky as dark today as it was when its first inhabitants looked skywards tens of thousands of years ago.



9 Starbugs on the glass focal plate of the UKST. Each 8 mm diameter vacuum-adhered "bug" contains an autonomous positioning robot, three metrology fibres (illuminated) and a science-fibre payload. (A Green)

"The sky is as dark as when the first inhabitants looked up thousands of years ago"

Today, remoteness is no guarantee of dark skies, and the light-plumes of cities can certainly be detected low on Siding Spring's horizon. But in 1990, state legislation was enacted in New South Wales to protect the observatory's skies by regulating lighting installations out to 100 km from Siding Spring. Almost a decade later, the observatory's Dark Sky Committee was formed to update the regulations in the light of technological and legislative changes, a process that came to fruition in 2016 with the introduction of a comprehensive new lighting code. In parallel with this work, the Dark Sky Committee spearheaded a proposal to have the adjacent Warrumbungle National Park recognized as Australia's first Dark Sky Park. This culminated in the award of Gold Tier Status by the International Dark Sky Association, also in 2016. As well as promoting tourism in the area, the Dark Sky Park will also help maintain the pristine skies of the observatory.

Epilogue

It is now more than a decade since the AAT was feted as the first-ranked 4 m telescope in the world. The ranking covered both productivity (number of papers) and impact (number of citations), with 2.3 times as many citations as its nearest competitor (Trimble & Ceja 2007). Moreover, at the time, the AAT was ranked just fifth in productivity and impact among optical telescopes of *any* size, on the ground or in space.

What is remarkable about those figures is that they were achieved not when the telescope was in its first flush of youth, but relatively late in its life. They demonstrated the efficacy of the large-scale survey strategies set in place in the mid-1990s, when 2dF was being commissioned. While the international landscape today is somewhat different, with a number of telescopes poised to carry out similar work, those performance figures hold out the promise that the AAT will remain productive for a much longer period than is currently guaranteed. With the continuing commitment and loyalty of astronomers past and present to the AAO, that promise is bound to be fulfilled. ●

AUTHORS

Fred Watson AM is head of Light and Environment at AAO, and holds adjunct appointments at Sydney University, UNSW, USQ, WSU, QUT and Macquarie University. **Jane Urquhart** is director of AAO, and head of the Science and Commercialisation Policy Division of the Department of Industry, Innovation and Science, Australia.

ACKNOWLEDGMENTS

A great many people have contributed to the work reported in this article. A number of key individuals in the Australian government, DIIS, AAL and the universities have put in an enormous amount of effort in brokering the partnership with ESO and the AAO transition. Also noteworthy is the work of the AAO Transition Team and the DIIS Optical Astronomy Group. We thank Emmi Mikedakis, Matthew Colless and Mike Steel for helpful comments on the article, and Warrick Couch and Neville Legg for earlier discussions. Perhaps the biggest thank you should go to the staff of the AAO, for their extraordinary achievements in the day-to-day running of the facility, and their forbearance in what is unquestionably a difficult period.

REFERENCES

Australian Academy of Science 2015 *Australia in the Era of Global Astronomy: the Decadal Plan for Australian Astronomy 2016–2025* (Canberra)
Cannon R & Malin D (eds) 2011 *Celebrating the AAO Past, Present and Future* (Australian Government)
Gascoigne S C B *et al.* 1990 *The Creation of the Anglo-Australian Observatory* (Cambridge)
Hoyle F 1982 *The Anglo-Australian Telescope* (University College Cardiff Press)
Trimble V & Ceja C A 2007 Productivity and impact of astronomical facilities: a statistical study of publications and citations *AN* **328** 983
Watson F & Colless M 2010 *Astron. & Geophys.* **51** 3.16