Mid-term review – ESO and ELTs

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1 Executive Summary

Access to optical/infrared 8m telescopes for observing and technology development delivers essential 'bread and butter' science covering all the key items in the 2016–2025 Decadal Plan and will be essential for nearly all major discoveries. Membership of the European Southern Observatory (ESO) was a number one goal of the current Decadal Plan. Accession to ESO via the limited term partnership is a major success of this plan and continued membership of ESO is a natural fit for the Australian model of astronomy.

Over the next five years we should make the most of the ESO opportunity and positively engage and secure ESO contracts with the anticipation that full ESO membership would be decided at the next Decadal Plan.

Extremely Large 20m+ Telescopes (ELTs) offer 'bigger and better' capabilities that will address the questions at the frontier of current Decadal Plan priorities. However, they will not be available until the next decade. The two ELT options for Australia are Giant Magellan Telescope (GMT) and the European Extremely Large Telescope (E-ELT) and both should be developed for now as they allow Australia to develop its strength in optical instrumentation, to capitalise on past investment and to mitigate risk. By 2025 it should be clear which of these options are viable and whether one, or both, should be pursued.

This is a first draft to prompt town hall discussion. It is expected to be updated during the mid-term review process.

2 Science Overview

As we enter the 2020s the 6-10m class optical/near-infrared telescopes (hereafter we will just say '8m telescopes' for the size class) have now become the key workhorse instruments of ground-based astronomy. By 'workhorse' we mean generally:

- They provide flexible, common user instruments covering a wide variety of modes to a broad audience
- They offer observational capability, today, of everything from objects in the nearby solar system to the depths of the z>10 Universe
- They support observational programs scaling from a few hours up to large surveys of hundreds of nights.
- Telescope time is allocated by an open proposal model based on scientific merit.

- Support is provided for users at a variety of skill levels in a 'national observatory' type model, including provision of observing support and post-observing support including data analysis pipelines.
- Just about any research group or research project will include some component of 8-10m telescope observing.

In contrast over the last decade the role of 4m telescopes such as the AAT has been gradually transitioning from their former workhorse roles to more specialised ones. These generally involve fewer instruments, fewer instrument changes and more blocks of nights dedicated to particular projects and large surveys. They have also supported more innovative and testbed instrumentation technologies. This specialisation has allowed them to remain extremely productive, but not cover the same broad science areas.

Australia now receives the majority of its 8m time on the four 8m telescopes known as the Very Large Telescope (VLT) of the European Southern Observatory (ESO). This was a top recommendation of the current Decadal Plan and has been successfully implemented by Australia forming a Limited Term Partnership with ESO. This has replaced a period of instability in Australian 8m access, where we withdrew from the Gemini partnership in 2015 and then had a series of short-term arrangements to purchase time on Magellan, Subaru and Keck telescopes. Arrangements with these other telescopes, through AAL, have now ceased due to funding constraints and balance against other portfolios.

Australian astronomers do still receive time, via various channels and private partnerships, on other 8m telescopes such as Subaru and Keck which also implement most of the features described above for the 'workhorse model'. This may continue but is not a question for this white paper. *For national 8m access we have now committed to ESO.*

The Limited Term Partnership gives us access to La Silla and Paranal Observatories (i.e. VLT) and participation in ESO funding and projects related to those. It does not include access to the Atacama sub-mm Array (ALMA) nor E-ELT related projects. This would come with full membership. It should be noted that the La Silla access includes the 4m class optical telescopes there, however they have an extremely limited instrument set now and blocks of nights are dedicated to campaigns and/or private projects.

Extremely Large Telescopes (ELTs) are now being developed. For the most exciting and difficult observations resulting in the greatest discoveries ELTs will be critical as they probe a new sensitivity space. Of particular interest to Australia are (i) the 24m GMT, because we have made a major $80M investment to become a partner and, (ii) the E-ELT which is a 39m telescope being built by ESO. ELTs are unlikely to become a workhorse, even in the next decade, because the nights are expensive and will be in limited supply due to the scale and cost of the facilities. Instruments will also scale up to be big and expensive, this combined with the reduced number of foci compared to 8m telescopes means there will be far less diversity in instrument choice.

3 How does the science connect with the priorities set out in the Decadal Plan?

When the Decadal Plan was written, a table was produced marking which facilities would contribute to which of the six key scientific questions (see Table 1). 8m and ELTs

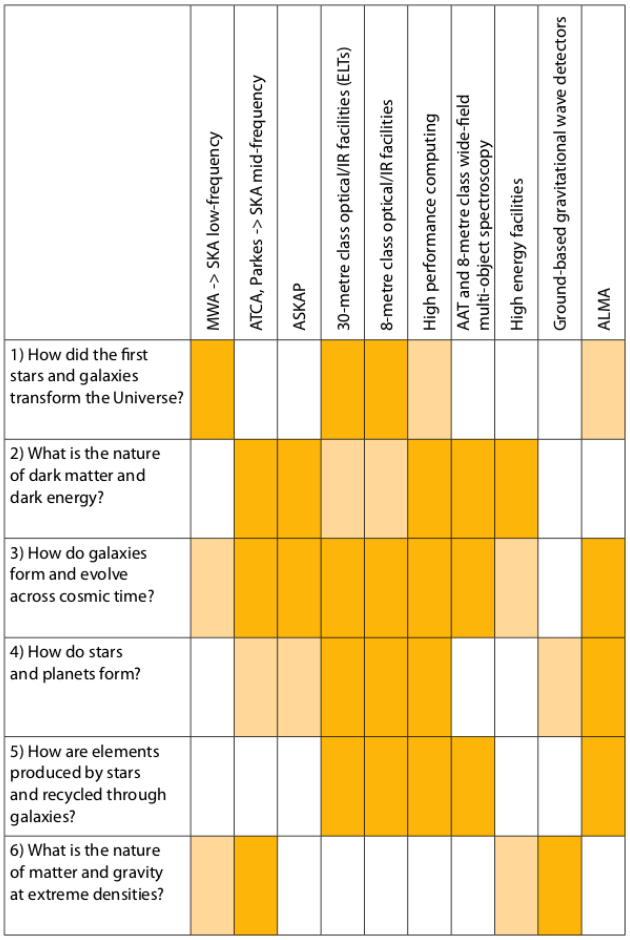

Table 1. Major national and international facilities required to answer the fundamental questions outlined in this Decadal Plan. Dark and light shading represent critical and supporting capabilities within the Australian astronomical context.

Caption and Table reproduced for convenience from Table 7.1 in'Australia in the era of global astronomy, The decadal plan for Australian astronomy 2016–2025', © The Australian Academy of Science 2015.

contributed to essentially all of them, both being marked as critical facilities in four cases and supporting in one case.

Below we list the six key scientific questions, and we summarise and illustrate how VLT and ELTs will contribute. The following is indicative but not exhaustive.

Q1) How did the first stars and galaxies transform the Universe? [DP: *critical*]

Primitive stars in the Milky Way and Local Group offer the most direct view of star formation and element production in the early Universe, and 8m observations are necessary for collecting data with the required detail and quality. Direct observations of galaxies and AGN in the epoch of reionisation will allow us to look at their structure and measure their redshifts. To do this work in the near-infrared by imaging and spectroscopy, 8m observations will be vital but ultimately the sensitivity and resolution of ELTs will be critical. ALMA is also proving a critical facility, especially for redshift measurement, and would be an invaluable benefit to this scientific question if Australia were to become a full member of ESO.

Q2) What is the nature of dark matter and dark energy? [DP: *supporting*]

8m telescopes were tagged as supporting this science question in the DP as it was envisioned the strongest constraints would come from very wide area cosmological redshift surveys (4MOST, Euclid, WFIRST, DESI). However, it has turned out that 8m telescopes are now also providing a crucial role. For example, the current cosmological frontier has turned out to be resolving the tension in Hubble's constant, and 8m

observations are proving vital here by providing key spectroscopic data on systems like gravitationally lensed QSOs for time delay measurements. They also allow spectroscopic follow-up of events such as supernovae and neutron star mergers at greater distances than can be reached by 4m telescopes, thus probing the full history of the cosmological expansion. High signal-to-noise spectra also allow classification which is critical for reducing systematic errors. In the future we also expect great contributions from ELTs via measuring even fainter transients at ever higher redshifts.

Q3) How do galaxies form and evolve across cosmic time? [DP: *critical*]

This is now bread-and-butter 8m telescope science. Normal galaxies emit most of their light in the UV/optical/NIR, and a vast literature exists on the evolution of these properties across redshift using imaging and spectroscopy. One of the frontiers is looking at the evolution of galaxy structure using high-resolution integral field spectroscopy at high redshift (z>1) where only 8m telescopes have the required sensitivity and resolution (via adaptive optics). While the proposed Square Kilometre Array, which will be the world's largest radio telescope, will struggle to detect galaxies at z>1, optical observations are now reaching z=10 (we note that ALMA is too). For nearby galaxies the integral field observations are pushed to the extreme, allowing exquisite mapping of nearby galaxies. Australia is now the lead for a next generation integral field spectrograph which will take advantage of VLT adaptive optics.

Q4) How do stars and planets form? [DP: *critical*]

While observations of the earliest dust-shrouded stages of star formation require far-IR or radio observation, later stages in star and cluster formation are accessible in the optical to Mpc-scale distances. Stellar populations are a strength of large (8m and ELT) telescopes, and as adaptive optics improves the gain goes as D^4, allowing fainter stars to be imaged at extreme distances. AO also enables spectroscopy at higher spatial resolution, and together this offers a detailed view of resolved stellar populations at larger distances and in more crowded regions.

Exoplanet discovery requires the high spatial and spectral resolution offered by 8ms and ELTs. An increasing amount of increasingly sophisticated instrumentation is being built for these, and this includes VLT, that could allow the routine discovery of exo-Earths.

Q5) How are elements produced by stars and recycled through galaxies? [DP: *critical*]

The abundances of stars across time and location in a galaxy are snapshots of the process of element production. 4m telescopes are currently producing large volumes of stellar abundance data in the Milky Way, but extending this work across the Local Group requires 8m telescopes.

Probing the interstellar and intergalactic diffuse media is done via their absorption and emission. Historically, bright sources have been used as absorption line probes. This is now everyday 8m science as their larger light gathering power has allowed higher-resolution probes and new kinds of 'backlights' (for example, lensed QSOs and even complete Einstein rings). With the ELTs we expect to be able to use fainter normal galaxies at z>2 to probe the intergalactic medium along the line of sight in absorption.

Because they are abundant, this will allow 3D tomography of the IGM, facilitating a new understanding of its cosmological evolution.

The new generation of 8m integral field spectrographs have allowed also to start to probe the intergalactic medium in emission via optical lines. For example, the MUSE and KCWI integral field spectrographs on 8m telescopes have revealed the circumgalactic media surrounding bright QSOs, being illuminated by the bright central source. Again, as we progress to ELTs we will be able to use fainter objects and see more of the cosmic web illuminated and be able to compare its structure with the detailed predictions that theory has made.

Q6) What is the nature of matter and gravity at extreme densities? [DP: *not flagged*]

This was not flagged in the DP for 8m telescopes as it was seen as the domain of multi-messenger astronomy and the forthcoming anticipated discovery of gravitational waves. Now we live in the post-GW170817 era and it has turned out that 8m telescopes provide a critical supporting role, especially for events involving neutron stars which require optical telescopes to identify transients and secure redshifts. This is critical 'homework activity', as we might expect for a workhorse facility. 8m telescopes do have impact on this question, and also on cosmological questions, as these redshift measurements are vital to using gravitational wave events to measure Hubble's constant (using them as 'standard sirens').

As enhanced gravitational wave detectors in the next decade push down in sensitivity and out in distance, larger optical telescopes will be required to follow up their optical counterparts.

In summary it has now become clear that 8m telescopes and ELTs are critical to essentially all the scientific questions in the DP. The exact boundary between 8ms and ELTs will move with time as the frontier on all these questions moves to higher resolution and fainter and more distant objects.

4 What are the current issues and key risks?

The accession to a limited term ESO partnership is a key success of our DP and delivers on the stated goal of having 30% of the nights of an 8m telescope for Australian science. ESO time is expected to accrue roughly with the size of the member state and our official 'net national income-based share' is 7.5% (2017 number), so with four 8m telescopes in VLT that box is ticked.

The limited term is from 2018–2028. After that Australia must become a full member or leave ESO, because the arrangement is regarded by ESO as an on-ramp for Australia to join ESO. There will not be a second limited agreement.

The Australian astronomical community is highly innovative and engaged, and we think there is no real risk that the community 'won't use ESO'. Already we have seen large numbers of proposals submitted with a success rate as high as that of long-established members. This is a good sign given that our 8m access has been so fluid over the last decade.

However, for an ESO renewal to happen, the Australian government is likely to need to see considerably more than science return. They will also want to see ESO being a catalyst for technology R&D in the community, for skills training, and to see contracts coming back from ESO to Australian companies and universities for items such as high-tech instrumentation. ESO-related R&D should then transfer to the commercial sector.

The key risks in our view are:

1) That the technological return and broader impact from membership of ESO do not live up to government expectations.

2) That there is insufficient engagement by or with Australian industry.

3) That the cost balloons out due to ELT construction and the cost to join ESO becomes unaffordable.

For our R&D program to be successful, the new AAO (with Macquarie, Sydney and ANU nodes) must succeed in the ESO model for instrumentation development. In this model ESO pays for hardware but the instrument-building consortium or national lab pays for labour. We are in the fortunate position that $5M p.a. of NCRIS funding is being directed to support this for the next few years. Clearly this, or some other funding source, must be found ongoing. Another fortunate position is that AAO has been selected to lead the next VLT instrument, 'MAVIS', which will be a visible light AO imager/spectrograph relevant to all six science questions of the DP.

What is a critical risk is that Australian ESO instrumentation projects must succeed, i.e. they must be built on a time and budget commensurate with such large projects. This is non-trivial for highly complex instrumentation projects and requires focus and management. AAO has recently gone through a major restructure. Under the transition AAO is receiving support from the National Collaborative Infrastructure Scheme, via Astronomy Australia Ltd., to provide an optical/infrared instrumentation capability for ESO and ELTs. It is vital that future AAT projects that AAO might be involved in are properly costed and funded so that they do not distract from the ESO/ELT mission. The best scenario is that they enhance this mission, for example by providing a low-risk testbed for new technologies being developed for larger telescopes.

Another issue is to ensure that the wider benefits of ESO membership (contracts, R&D support) are delivered more widely in the community than just the three AAO nodes. This will be critical for any case for full membership.

Turning to ELTs, the risks and benefits are harder to assess. The three ELT projects GMT, E-ELT and the Thirty Meter Telescope (TMT) have schedules driven by funding. The E-ELT is the most secure here, as it is developed within the framework of the large ongoing and secure ESO budget (we note that this is not quite enough, which is why ESO has been adding new members). E-ELT first light is listed as 2025 but will likely slip because of funding limitations.

GMT and TMT are U.S. projects and the U.S. is at present going through its own decadal planning process for the 2020–2030 period. GMT and TMT have put in a joint submission, with a vision that the U.S. National Science Foundation (NSF) will make a major construction investment in both if ELTs are ranked as the highest-priority ground-based project. This would put both telescopes over a threshold at roughly ~70% funded. They would still need to seek additional private funds, but at that point they

would be likely certain to be built in some fashion. There is additionally a significant risk to the TMT in the issues surrounding Mauna Kea, and this may indirectly impact on GMT via NSF.

As Australia has made an investment in GMT, we should continue to support that project to try and realise construction. It should be noted that further investment in that project by others would reduce Australia's notional share, which is likely to end up at around 5%. However, 5% of a functioning telescope is better than one not being built at all. We should also continue to develop the ESO engagement so that full ESO membership would provide long term 8m access, and as a bonus generate E-ELT access.

There may be future investment decisions to be made with regard to GMT (e.g. increased share) vs ESO (e.g. full membership). It is premature to make a call here, but it is interesting to note that the two telescopes are both in the south and offer complementary capabilities. E-ELT with its larger mirror will be better for the faintest targets and highest performance and resolution adaptive optics observations. GMT offers a field-of-view several times larger and a deep multi-object capability well matched to Australian science interests.

E-ELT instruments offer a clear engagement opportunity but also a risk as they place us in a catch-22 situation. A large fraction of future contracts will be for E-ELT related work. To be eligible for these Australia must be a full member; however, we can only hope to be a full member if we receive contracts. It would be helpful to have clarity on E-ELT opportunities for Australia over the next 5 years.

A final point is that instrument projects for telescopes of this class are now 7–10 year projects. If Australia is to build GMTIFS, MANIFEST, MAVIS and others then it is highly desirable to retain telescope access post-2025 to access them to do science (noting that the guaranteed time would still be available).

5 What are the synergies with other Decadal Plan Priorities?

Clearly the priorities *'Partnership equating to 30% of an 8-metre class optical/IR telescope*', '*Partnership equating to 10% of a 30-metre class optical/IR extremely large telescope'* are addressed.

There is a strong synergy with '*operations of the SKA precursors ASKAP and MWA… and membership of the SKA telescope* '. Optical observations tell us about the stars and ionised gas across redshift (and the redshift itself at greater sensitivity than radio), whereas radio frequencies probe HI gas reservoirs, non-thermal emission from supernovae and black holes. ALMA is also vital to probe cold molecular gas (and ALMA access will come with full ESO membership). That said, continued operation of the AAT for wide-field spectroscopy has an even larger synergy due to the survey capability.

Continued participation in ESO/ELTs is vital for *'AAO and ATNF to maximise Australia's engagement in global projects through instrumentation development for these and other observatories, and to manage and facilitate Australian engagement in international telescope projects'.*

They are also relevant to '*Utilisation of astronomy to help improve the participation and standard of science education'* (well organised ESO outreach programs that Australia can

partake in), *'Provision of graduate and postgraduate training that includes transferable skills'*, (e.g. ESO Fellowships) and '*establishment of a central body to promote and facilitate industry engagement, ensuring that Australian industry benefits from opportunities facilitated by the next generation of global facilities*' (the government has already made industry engagement appointments for ESO).

Another priority here is the '*adoption of principles and practices that achieve at least 33% female representation at all levels of Australian astronomy by 2025 in alignment with the current PhD student cohort';* here, our perception is that Australia is pioneering best practices and we have an opportunity to influence ESO and other members resulting in a big international impact. This is already being rolled out, for example in blinding of telescope time applications.

6 What is the best engagement model likely to be?

Australians need to engage in European collaborations to make high productivity use of ESO facilities and embed themselves in technological collaborations (hardware, software, data science) that will lead to new instrumentation projects and commercial spin-offs. In particular, we need to pay attention to the instrumentation and technology roadmaps for future VLT instruments, and also E-ELT ones. Australia has been selected for Phase A of MAVIS, and there is also a lot of interest in the BlueMUSE instrument.

We should also develop the concept of a 'southern wide field spectroscopic large telescope'. This is envisioned as an 8-16m telescope with a >1º field of view, similar to the Maunakea Spectroscopic Explorer project in the north. There has been considerable discussion in the ESO community about this as the next project after E-ELT. It would suit Australian scientific and technical expertise extremely well and would have excellent synergy with SKA and LSST. This would supersede the wide-field capability of the AAT, which is currently still the best in the southern hemisphere. Development of this telescope may provide an interesting method of in-kind buy-in for full membership.

In the current model, Australians will be expected to travel to Europe frequently, which may be difficult for some and has a high carbon impact. We should strongly encourage more use of video-conferencing type technologies in the ESO community, which has historically relied on the 'everybody flies to a one-day meeting in Garching' model. Chile is a natural ally in making this transition. Similarly, ESO's 'Designated Visitor Mode' for remote observing could be improved, which would take advantage of Australia's time zone (observing during the day) and would be highly engaging for students.

We should endeavour to hold an ESO conference every year and budget to assist key European science collaborators to visit, potentially through existing funding sources such as Astro3D and OzGrav).

We should continue to engage on all the important committees, including ESO Council, Scientific Technical Committee, Users Committee and Observing Programs Committee.

We should emphasize and market to ESO our community's strong astro-software and data science capability, which goes well beyond the AAO Data Central node and is a critical item for all future instruments.

With all the ESO focus we should not lose sight of GMT. If ELTs are selected as the priority in the U.S. Astro2020 Decadal Plan, then the GMT and TMT projects could move rapidly toward construction. Our science engagement in GMT has been somewhat hampered in recent years, as there is strong science overlap between Magellan and GMT partners, and we are no longer Magellan users. Ensuring GMT engagement will require active management to ensure that workshops and science planning meetings are attended. Our instrumentation engagement in GMT is healthy with two large projects (MANIFEST and GMTIFS). This needs to be sustained.

7 What are the approximate costings?

Under the terms of the limited term ESO agreement, which provides access only to La Silla and Paranal observatories ('LPO'), we are currently:

1) Paying $12M a year until 2028 for operations costs and LPO depreciation. This is being paid by the federal government.
2) Likely to need to sustain around $5M p.a. until 2028 to pay labour costs associated with preserving our national optical instrumentation capability in the AAO. This is currently funded by NCRIS via AAL.

Full membership would be expensive, and it is highly uncertain to make an estimate for 2028. **To illustrate the scale of the costs we re-quote the numbers below for joining in 2015 from the Decadal Plan:**

1) $110M joining fee for capital cost (we note that in the 2015 plan the AAT was considered as a 25% in-kind contribution).
2) $18M p.a. in operations costs.

Extrapolating this to 2028 is clearly quite uncertain, because we would have to incorporate changes in Australia's economy and 'net national share', the EUR/AUD rate, indexation and the total ESO budget, etc. The AAT is very likely to not be viable as an in-kind contribution in 2028. The joining fee would be reduced by some of the current limited term payments (i.e. the LPO depreciation component, which would be about 30% of that budget).

To be conservative, we would probably allow a factor of 2 uncertainty. At any rate, the sums are so large that it would be the subject of direct, confidential negotiation of the federal government with ESO and would not be a 'sum of money that the community needs to find'.

It is possible that Australia could make a considerable in-kind buy-in via a project such as the wide-field Southern Spectroscopic Telescope, for example if Australia were to provide a $50-100M class focal plane. This would have considerable merit with the Australian government, though it should be noted that delivering E-ELT first is the ESO priority. E-ELT instruments exploiting Australian R&D could likewise count, and this may be a way around the catch-22 mentioned above. It is possible that the 25% in-kind limit could be waived, given the need to get E-ELT built.

What are the benefits of full membership? First there is 'access' to observing time on all the facilities LPO+E-ELT+ALMA. This has a variety of meanings, noting first that the VLT

currently operates under an 'open skies' policy, meaning that observing proposals from ESO members do not normally have a preferred status compared to non-members. The only qualifier is that member proposals are selected by the OPC in the event of ties. ALMA operates under more restrictive rules benefiting members, and E-ELT time allocation policies remain to be determined. A key issue for the latter is what the other ELTs do. All future time allocation policies are determined by the ESO Council, and on a ten-year timescale they could very well change significantly.

Next there are the benefits of full support and access to ESO opportunities including fellowships, travel funding, training, and access to technology R&D projects and contracts (e.g. for new instruments) to the member states. This is of course what the Australian government is mainly interested in. Such projects in optical astronomy would bring huge benefit to the AAO nodes. It would be unrealistic to expect every institution in Australia to benefit from these optical opportunities, just as it is unrealistic to expect every institution to benefit from the SKA. However, it should be wider than simply the current three AAO nodes. Expansion of the AAO nodes to tap complementary and enhancing capabilities at other institutions, rather than duplicating and competing on these, would be a natural way to handle this.

Finally, we would like to close on the broader picture: the vision for ESO is that member states, no matter how small, can work together to deliver scientific facilities second to none and available to everyone. This shared scientific community is a natural fit to a nation such as Australia where we have had a long collaborative tradition in astronomy.

Clearly the final decision on full membership rests with the 2026–2035 Decadal Plan, though we cannot entirely wait as we need to start working the case for full membership now.