ASTRO 3D

ASTRO 3D MID-TERM REVIEW SUBMISSION

ARC CENTRE OF EXCELLENCE
FOR ALL SKY ASTROPHYSICS IN 3D

Australian Government
Australian Research Council

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EXECUTIVE SUMMARY

The ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D/A3D) is building the first comprehensive picture of how the ionising radiation, matter, and chemical elements in the Universe formed and evolved from the very first stars in the infant Universe to our own Milky Way, spanning 13 billion years of cosmic evolution.

Our discoveries are being made by combining state-of-the-art theoretical simulations, using Australia's supercomputing facilities, with ambitious observational surveys that include the epoch of reionisation survey using the Murchison Widefield Array, large 3D hydrogen surveys using the Australian Square Kilometre Array Pathfinder, 3D galaxy evolution surveys using the European Sothern Observatory, 3D optical integral field surveys of 15,000 galaxies using the Anglo-Astralian Telescope, and a Galactic Archaeology program to track the chemical history and accretion history of our Milky Way. Australia is a stakeholder of two of the next-generation telescopes: the Giant Magellan Telescope and the Square Kilometre Array, and Australia is a strategic partner of the European Southern Observatory (ESO) which is building the largest optical telscope in the world. We designed our surveys and projects to use Australia's pathfinders for these massive next generation telescopes, providing critical training for our ECRs and students.

This report describes the progress and discoveries made in the first half of ASTRO 3D, an update on our far-reaching equity and diversity programs, and our nationwide education and public outreach programs.

"I really enjoy being part of ASTRO 3D – I've never really been part of something like this before. I really love how it brings together astronomers from a variety of different fields. I find myself collaborating with astronomers, scientifically, that I normally wouldn't be able to. It's really opened up my horizons, for who I actually collaborate with."

ASTRO 3D postdoc Nichole Barry, University of Melbourne

1. CENTRE'S ACHIEVEMENTS AND PROGRESS AGAINST OBJECTIVES OF THE ARC CENTRE OF EXCELLENCE SCHEME

A. HIGHLY INNOVATIVE AND TRANSFORMATIONAL RESEARCH

Our programs have significantly advanced our understanding of how the ionising radiation from the first stars transformed the early Universe, how the first stars and galaxies formed and evolved, and how galaxies like our Milky Way formed and evolved across 13 billion years of cosmic time.

Our **Genesis Simulations** are bespoke theoretical galaxy formation models to predict and interpret A3D surveys through close working relationships between observers and theorists. We are using Australia's national supercomputing facility, NCI, to run large cosmological N-body simulations to extract the assembly histories of the dark matter halo population and to couple these histories to semi-analytic models to produce synthetic galaxy populations across cosmic time. Our models are then used to create tailored 3D mock radio and optical datasets for direct comparison with our observations. We are now building hydrodynamical galaxy formation zoom-in simulations of galaxy-mass systems to understand how predictions are sensitive to the choice of galaxy formation prescription and to study outflowing material from galaxies.

To understand the very first structures in the universe, we are conducting a multi-year survey to detect neutral hydrogen for the first time at the epoch of reionisation. This survey uses the **Murchison Widefield Array** in Western Australia, which has unmatched sensitivity on a radio quiet site**.** Our team has developed innovative methods to treat instrumental systematics, reduce noise, and remove foreground galaxies. These methods have improved our ability to detect the epoch of reionisation tenfold.

The first stars in the universe appeared 100-250 million years after the Big Bang. The radiation from these first stars ionised the surrounding hydrogen gas, causing the epoch of reionisation. While the first stars long ago exploded in supernovae, their direct descendants are still alive today in the Milky Way and we are searching for them. We have obtained spectra for several thousand first star candidates in the Milky Way and have discovered the top three most pristine stars.

We are using the Hubble Space Telescope and the world's largest ground-based telescopes to search for the **First Galaxies** that formed in the first two billion years of thhe universe. When the James Webb Space Telescope launches, we will pivot to using James Webb guaranteed time and Early Release Science programs to search for the first galaxies.

Our Galaxy Evolution project bridges the first galaxies with the present-day universe by tracking the mass assembly, chemical evolution and ionising radiation across cosmic time. We use a technique, predicted by Einstein, called gravitational lensing, where the most massive objects in the Universe (galaxies containing supermassive black holes and clusters of galaxies) bend the light from distant galaxies, creating a magnifying glass that can magnify galaxy images 10-30x in brightness as well as stretching the light to allow an unprecedented resolution to identify how mass and chemical elements are distributed across galaxies with time.

The Australian Square Kilometre Array Pathfinder (**ASKAP**) surveys WALLABY, DINGO, and FLASH will

track the evolution and build-up of neutral hydrogen gas in galaxies. These surveys are underway, and will cover three-quarters of the entire sky with unprecedented resolution and depth, mapping the distribution of gas and dark matter in over 600,000 galaxies. Our ASKAP surveys obtained 300 hours of pilot survey time before the formal start of the ASKAP surveys in 2020.

We have completed our **SAMI** 3D integral field spectroscopy survey of 3000 galaxies in the Local Universe. This survey has higher spectral resolution than the northern hemisphere MaNGA survey, making SAMI uniquely suited to analyse galaxy motions. We are currently building the next-generation 3D spectrograph, **Hector**, that will have capture more galaxies simultaneously at higher spectral resolution than ever before. With Hector, we will conduct a massive high-resolution 3D survey of 15,000 galaxies, opening unique windows into the stellar dynamics of lower mass galaxies and outflows of matter from galaxies.

Our **GALAH** galactic archaeology survey aims to obtain high-resolution spectroscopy of 1 million stars within the Milky Way Galaxy to reconstruct its formation history with precise stellar elemental abundance patterns, ages and kinematics. We have surpassed our half-way mark, with spectra of 600,000 stars in-hand.

Our surveys and projects have achieved many scientific discoveries and have met or surpassed their milestones for the first half of the Centre. Highlights include:

- We simulated the epoch of reionisation. UWA postdocs Rhys Poulton, Lucie Bakels and Pascal Elahi developed new algorithms for structure finding, tree-building, and accurate characterisation of sub-halo trajectories, while U.Melbourne postdoc Simon Mutch developed a code (called Meraxes) that self-consistently couples ionising sources to the large-scale distribution of neutral hydrogen.
- Melbourne postdoc Nichole Barry produced the most stringent upper limits on the spatial scales for the structures at the epoch of reionisation. She and the epoch of reionisation team improved our ability to detect the epoch of reionisation by a factor of 10.
- ANU postdoc Thomas Nordlander found the most iron-poor star in the Universe, and our team discovered an extremely pristine star that is strongly enhanced in r-process elements, most likely produced by a hypernova in the infant Universe.
- CI Michele Trenti and postdoc Rachel Livermore used Hubble Space Telescope data to characterise the galaxy luminosity function during the epoch of reionisation. First galaxy candidates are now being characterised in the infrared, optical, and sub-mm using NASA's Spitzer Space Telescope and the ESO VLT and Keck telescopes. Genesis PhD student Keven Ren and postdoc Simon Mutch from Melbourne are making theoretical predictions for these first galaxy candidates.
- The Galaxy Evolution team, led by CI Kim-Vy Tran is obtaining deep spectroscopy on the ESO VLT and Keck. They have so far confirmed over 70 lensed galaxies. The full dataset will be released once complete. Swinburne PhD student Colin Jacobs discovered a unique gravitionally lensed system called The Rosetta Stones, where a low mass elliptical galaxy, over 10 billion light years away was magnified 22 times. Swinburne ASTRO 3D Fellow Tiantian Yuan discovered the most distant spiral galaxy, and the most distant ring galaxy, analysed with Genesis simulations by UWA postdoc Ahmed Elagali and UWA ASTRO 3D Fellow Claudia Lagos.
- Affiliate Charlotte Welker used our SAMI survey to make the first measurement of the kinematic alignment of galaxy spin with large-scale structure.
- In GALAH, ANU AI Sven Buder dissected the discs of stars and measured their ages, velocity, and location. Sydney AI Sanjib Sharma revealed the fundamental relations governing the velocity dispersion of stars regarding their age, angular momentum, and chemical composition. UNSW AI Sarah Martell showed that giant stars require multiple formation channels to generate their lithium abundance.

"In a Centre of Excellence like ASTRO 3D, having such a big diverse group of people working on such a broad range of sciences is really challenging, but at the same time, one of the best opportunities of working on something like ASTRO 3D is the opportunity to speak with such a broad range of people and bouncing ideas off all of them and having the opportunity to collaborate with them."

ASTRO 3D Genesis postdoc, Simon Mutch, University of Melbourne

Thanks to scheduled cross-node discussion sessions at our science meetings, workshops, state node lunches, and busy weeks, collaborations across projects and nodes are now the norm within ASTRO 3D. One of the main goals of the Centre is to facilitate direct collaboration between theorists and observers. Highlights include:

- With the UWA and U.Melbourne Genesis team, Curtin PhD student Bella Nasirudin has modelled the astrophysical sources along the light cone and observed them with a model telescope to mimic our epoch of reionisation data. The Genesis and Epoch of Reionisation teams are collaborating closely on modeling the neutral hydrogen signal from the epoch of reionisation.

- The First Stars team at ANU collaborates with the Genesis team in Sydney and WA to connect the oldest stars' orbits in the Milky Way halo with the early merger history of the Milky Way. Our state-of-the-art 3D radiative transfer and line-formation calculations can produce model spectra which can be used to analyse critical elements, such as hydrogen, oxygen and iron. Through this collaboration, ANU PhD student Ella Wang published the first 3D non-local
- thermodynamic equilibrium line profiles for lithium.
- UWA postdoc Lilian Garratt-Smithson and the FLASH teams use Genesis simulations to predict the HI properties of the ASKAP galaxy population.
- Genesis PhD student Kate Harborne and SAMI postdocs Jesse van de Sande and Sam Vaughan used Genesis simulations to develop new ways to correct kinematics for beam-smearing caused by atmospheric motions. They calculated the likelihood of a galaxy being a fast or slow rotator in the spin-mass plane using a Bayesian mixture model.
- The SAMI team is also collaborating with the GALAH team to identify Milky Way analogues in the SAMI data and model the appearance of the Milky Way if observed from outside the Milky Way.
- Melbourne First Galaxies PhD student Alex Cameron collaborated with Galaxy Evolution and SAMI researchers from ANU, Swinburne, and Sydney to analyse the first galaxy analogs from the SAMI survey.

An essential outcome of the Centre is our massive public data releases, which facilitate enormous ranges of research beyond the science conducted within ASTRO 3D. Data delivery highlights include:

- CI Darren Croton developed the Theoretical Astrophysical Observatory, a public data portal for the delivery of galaxy formation model predictions. UWA researcher Kate Harborne developed new software tools for comparing simulated and observational datasets called SimSpin that is also publicly available.
- Our MWA team, led by CI Cath Trott, published the world's largest epoch of reionisation dataset.
- The First Stars team obtained spectra for several thousand first star candidates in the Milky Way, with 500 of the most promising first stars candidates released to date.
- The SAMI Galaxy Survey dataset of 3000 galaxy data cubes and value-added data products was been released to the community in January 2021
- Our GALAH public dataset of 500,000 Milky Way stars is a world leader; it is by far the largest publicly available catalogue with ages and elemental abundances for multiple chemical elements of stars.

B. INTERNATIONAL STANDING

Our projects are highly competitive internationally, as demonstrated by quantitative measures. Our research focus on the epoch of reionisation and the formation and evolution of galaxies are recognised as critical by Astronomy Decadal surveys in the US, Europe and Australia.

ASTRO 3D programs have been awarded large amounts of observing time on the world most powerful telescopes, including the Hubble Space Telescope Keck, VLT, and ALMA ($124,540,000 worth).

First Stars and GALAH investigators Thomas Nordlander and Yuan-Sen Ting received 3.5 million and 20.5 million CPU hours on the new Gadi supercomputer at NCI through competitive peer review.

"ASTRO 3D enables cross-pollination of ideas and techniques that just doesn't happen outside the Centre framework. To me, this is the most exciting thing about being a part of ASTRO 3D"

ASTRO 3D AI, Nicholas Scott, University of Sydney

Our Centre researchers have produced 635 refereed publications in 20 journals with impact factors >2.5. These publications have accumulated 10,349 citations in just 3.5 years, including 3 Nature papers, 5 Nature Astronomy and 2 Science papers.

Our diverse team of researchers have won prestigious national and international awards, including the 2020 US National Academy of Science James Craig Watson Medal (Director Lisa Kewley), the Order of Australia (CIs Elaine Sadler and Rachel Webster), the 2021 Nancy Mills Medal for Women in Science (CI Cathryn Trott), the Astronomical Society of Australia (ASA) Louise Webster Prize for outstanding research by a postdoctoral scientist (ASTRO 3D Fellows Emily Wisnioski and Katie Auchettl), the ASA Charlene Heisler Prize for best PhD thesis (Adam Thomas), the 2019 ASA Anne Green Prize for a significant advance or accomplishment by a mid-career scientist (AIs Barbara Catinella, Mark Krumholz). AI Sergio Leon-Saval received the 2019 AOS John Love Award for Innovations and Technical Advances in the field of Optics for "his pioneering translational research on specialty optical fibres to optical communications and advanced astronomical instrumentation". AI Alan Duffy

won the 2018 Eureka Celestino Prize for promoting understanding of science, and our STARS Telescopes in Rural Schools Program, led by Education/Outreach Manager Delese Brewster and AI Brad Tucker won a Department of Industry, Science, Energy and Resources Maker Project - Community STEM Engagement grant. ASTRO 3D researchers have received prestigious ARC fellowships, including 5 Discovery Early Career Awards, 7 Future Fellowships, and a Laureate Fellowship.

C. LINKING AUSTRALIAN RESEARCH STRENGTHS

Linking Theory with Observation

We have built a successful model for rapid collaboration between theory and observation. A theorist is dedicated to every survey and project, enabling direct and rapid comparison between theory and observation, as well as theoretical predictions for our future observations. For example, Curtin and Melbourne MWA Epoch of Reionisation (EoR) teams work with Genesis ASTRO 3D fellow Brad Greig on astrophysical parameter estimation using the direct MWA EoR multi-redshift limits. Using the Genesis simulations, Curtin CI Cath Trott and PhD Bella Nasirudin are working with UWA. Melbourne theorists Chris Power, Simon Mutch, and Brad Greig to simulate realistic epoch of reionisation with foreground datasets in the presence of noise with a realistic instrument model to assess the loss of parameter estimation power with real instruments. Cross-project supervision of PhD students and postdocs facilitate these interactions.

Linking Radio with Optical

One of the main aims of our Centre is to connect radio and optical astronomers working on galaxy formation and evolution to trace all phases of matter in galaxies; hot gas and stars are traced in the optical, while cold gas is traced in the radio. We need 3D instruments to trace galaxy motions which tells us about the total mass in galaxies, including dark matter. S ydney CI Elaine Sadler and Oxford University AI James Allison are collaborating with ASTRO 3D optical astronomers to measure the optical properties of distant galaxies from the FLASH survey. The WALLABY and DINGO teams are collaborating with the Hector survey team to ensure that key radio galaxies are included in the Hector survey. SAMI PhD Student Lucy Hogarth used ALMA to follow up SAMI galaxies with massive outflowing winds. The ALMA data shows that galaxies with winds have a higher central concentration of molecular gas than regular galaxies.

Linking Data Science with Large Surveys

ASTRO 3D flagship telescopes are collecting unprecedented volumes of data, while the Genesis Simulations are producing prodigious amounts of theoretical data. These petabyte-scale data sets require sophisticated data management and access mechanisms and new algorithms and visualisation tools to extract scientific information efficiently.

Our Data Intensive Astronomy (DIA) program is developing efficient workflows and post-processing pipelines for ASKAP and MWA data processing to provide a common framework for the direct comparison between ASTRO 3D survey data and the Genesis simulations. We are also developing tools to ingest Genesis data into the Theoretical Astrophysical Observatory directly. Astronomy Data Central has funded pilot cross-matching, querying, and visualisation tools for ASTRO 3D data sets.

D.BUILDING CRITICAL MASS

From 2017 to 2020, our Centre has grown from 138 to 232 researchers (Figure 1). The main growth areas are PhD students, postdocs, and affiliate or associate investigators (AIs). The majority of this growth occurred prior to the addition of the three new nodes, which has increased the capacity of our Centre to meet our Science Goals through unique expertise, science leadership and postdoctoral researchers to be hired in mid to late 2021.

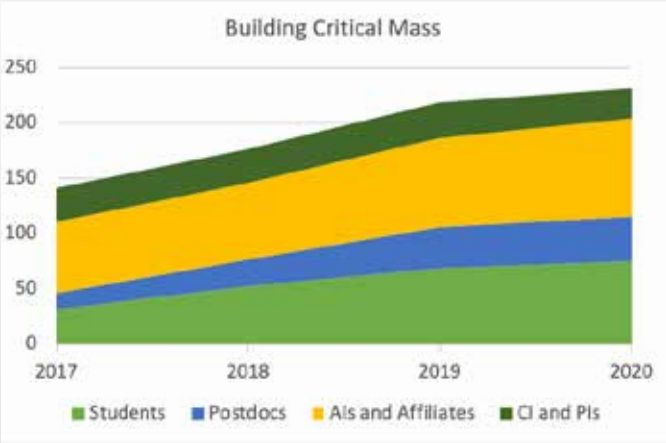

***Figure 1** - The change in number of ASTRO 3D researchers from June 2017 to Dec 2020*

E. COLLABORATIVE APPROACHES

ASTRO 3D has capitalised on Australia's research strengths by uniting our top national astronomical universities with Australia's national optical observatory (Anglo Australian Telescope at Siding Spring Observatory), Australia's national radio facility (CSIRO Centre for Astrophysics and Space Sciences) and Australia's National Supercomputing Facility (the National Computational Infrastructure; NCI). Our international partners bring a tremendous amount of expertise and resources, linking to crucial research programs in field and elevating ASTRO 3D to a truly global Centre with a sharp focus on internationally competitive and timely science goals.

In our events and communications, the focus is firmly on collaborative science across projects and surveys, not on the node universities. Whilst each institution provides an administrative home, our ASTRO 3D events, meetings and reports are science-focussed. ASTRO 3D Annual Retreats provide updates from all surveys and projects and cross-project discussion sessions that lead to many cross-project collaborations. Our Annual Science Meetings are focused on sharing exciting new science results with the entire team as well as collaborative

breakout sessions. Multiple nodes and partners in each survey attend regular in-person or on-line busy weeks, where concentrated collaboration activity is conducted towards specific scientific and data analysis goals. These meetings and events have resulted in collaborations between observers and theorists, between different projects and surveys, and the sense that ASTRO 3D is larger than the sum of its parts, providing more and richer opportunities than any individual institution can provide alone.

The cohesiveness of ASTRO 3D benefits tremendously from intertwined projects/surveys. Over the past three years, our surveys, projects and programs have become so deeply interrelated that we have moved away from dividing them into themes or threads which we feel creates artificial barriers. Our Survey/Project Leads drive the collaborations across our node and Partner Institutions, aided by Collaboration Leader Joss Bland-Hawthorn, who facilitates connections with international partners.

The author network of ASTRO 3D publications (Figure 2) shows our strong cross-project collaborations. Every ASTRO 3D project has more refereed publications with authors across other projects than internal (solely project-based) publications. Genesis has crucial links with all observational projects. ASKAP is critical for the Galaxy Evolution and the SAMI surveys. GALAH underpins work on the First Stars and the First Galaxies. This kind of cross-collaboration is crucial for properly understanding the cosmos, but is rarely possible without the support and scale of a collaborative Centre.

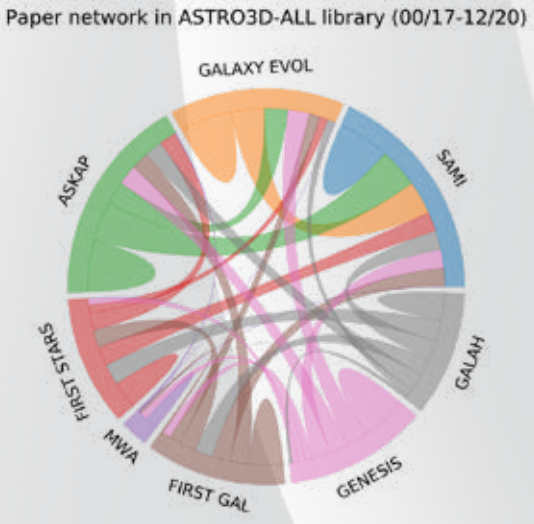

Figure 2 *- Interdependence and collaboration of ASTRO 3D projects, measured by publication authourship. Hill size represents internal (survey-only) publications while chord thickness represents the number of cross-project publications*

In ASTRO 3D, no project is focussed solely at any one node; nodes contribute to many projects (Figure 3). This fosters collaboration both within institutions (across projects) and across institutions (within projects). While the expertise at some nodes underpins a project (e.g., Curtin and Melbourne for MWA, or UWA on ASKAP), other nodes are powerhouses of activity; ANU,

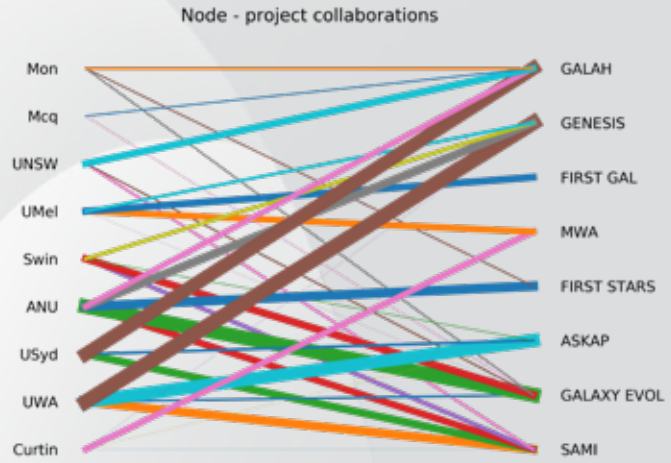

Figure 3 *- Collaborations between nodes (left) and projects (right), measured by publications. Line thickness represents number of unique publications by node members on a project*

Sydney, Melbourne, UWA, and Swinburne, have major collaborations connecting to many projects. Similarly, the galaxy evolution and SAMI survey unite every single node. First galaxies, the Genesis project, and the GALAH survey, all link nearly every node. These cross-node and cross-project publications are a strong reflection of the productive nature of collaboration in ASTRO 3D.

ASTRO 3D collaborations have also led to new Australia-wide projects. SkyHopper includes all six original ASTRO 3D nodes and new node Macquarie. The MAGPI survey is the first Australian-led VLT large proposal (340 hours). Led by our Fellows across five nodes, and across four surveys and projects, MAGPI will provide a rich dataset to the galaxy evolution community in Australia and internationally.

F. NEW RELATIONSHIPS AND NEW NETWORKS

In mid-2019, ASTRO 3D invited submissions from the Australian astronomical community for new nodes. In our call, we highlighted the Centre needs, including support for theoretical expertise for our Galactic archaeology program, leadership and personnel for our galaxy evolution program, and scientific support and instrument development support for the Hector instrument. We also emphasised the need for support for our Telescopes in Schools program. After an open and transparent process, ASTRO 3D has added three new nodes: Monash University, Macquarie University, and the University of New South Wales (UNSW). The addition of the new nodes brings in substantial scientific expertise and person-power, in addition to $1M in new cash for the Centre to help us achieve our ambitious science goals in the 2nd half of the Centre.

Monash strengthens the Centre in the critical areas of Galactic archaeology and SAMI data science. Macquarie University significantly strengthens the Centre in the critical areas of Data Intensive Astronomy and instrument development. UNSW provides leadership and expertise for the Galaxy Evolution program, and as leadership of the ASTRO 3D Equity, Diversity and Inclusion committee.

We are also adding two new International Partner organisations: the University of Hertfordshire which brings world-leading expertise in the chemical evolution of galaxies, and the University of Texas, Austin, which strengthens our first galaxies and galaxy evolution projects through new surveys with the upcoming James Webb Space Telescope and large ground-based telescopes.

G. BUILDING AND RETAINING AUSTRALIA'S HUMAN CAPACITY

Our Centre is a magnet for top PhD students and postdoctoral researchers from Australia and overseas. Our PhD student and postdoc cohorts have more than doubled over the first three years of the Centre (see Figure 1). One of our Centre goals is to build and retain a diverse group of young scientists who will lead the programs on the next-generation telescopes.

ASTRO 3D aims to reach 50/50 gender equity at all membership levels by the end of 2021. The Centre began with 20-30% women depending on level; we currently have 42% women. Our modeling indicates that we are on-track for 50% women by end of 2021. We have achieved the recommendations of the Australian Astronomy Decadal Plan 2016-2025, which recommended that astronomer institutions aim for 33% women by 2025. This fraction of women has been achieved through gender balanced search committees and gender balanced short-lists for all positions. We have also advertised and recruited into four women-only permanent positions.

We have introduced many initiatives aimed at retention, including offering all positions as part-time, family-friendly meeting hours, travel support for children and carers, women's leadership workshops, unconscious bias training programs, LGBTI ally training, cultural awareness training, 50% female attendees/ speakers/SOC for all workshops/conferences, 50% women nominated for awards, and Centre-wide mentoring circles. We have also modelled the Australian astronomical workforce, with targets and recommendations for retaining women published in a series of papers in Nature Astronomy.

We are training our diverse young scientists on the pathfinder facilities for the next-generation telescopes. Our Galaxy Evolution and SAMI projects build expertise in the 3D technology that will be the workhorse instruments on the next generation of ground-based optical telescopes. Our Australian universities are building 3D instruments for current and next generation optical telescopes (MAVIS for the ESO VLT, and GMTIFS and MANIFEST for the Giant Magellan Telescope), and ASTRO 3D galaxy evolution researchers are deeply embedded within the science development teams. Our first galaxies and galaxy evolution programs are also poised to use the James Webb Space Telescope through their leadership and membership of early release and guaranteed science programs.

Our MWA Epoch of Reionisation program is the prime training ground for the SKA. As an SKA pathfinder telescope, our MWA students and ECRs are learning interferometry and innovating new interferometric data analysis techniques that will be applied to the SKA. We are currently defining the observational strategy for the SKA Epoch of Reionisation experiment. Our initial work to identify the best SKA fields using our MWA datasets and metrics have been presented to the SKA Science Working Group, and we are testing the MWA fields for SKA science. Our ASKAP surveys are helping build big data capability within the Australian SKA Regional Centre. We have developed international SKA collaborations towards this effort; recent visits by the Canadian and Spanish SKA Science Directors have led to a combined project between the Spanish and Australian SKA Regional Centre to supply database resources to ASTRO 3D for the WALLABY survey.

Through our partnership with NCI, our models utilised millions of hours of NCI verification time. We also obtained external HPC cycles through peer-reviewed allocations. These joint ventures with the supercomputing industry create opportunities to increase Australian astronomical theory and simulation capacity and to bolster international competitiveness in theory.

ASTRO 3D students and ECRs are involved with the Hector instrument design and development and the concept design and early development of SkyHopper, an Australian-led international infrared miniaturized space telescope, with rapid-response capabilities optimized for photometric redshift determination of gamma ray bursts during the epoch of reionisation. These projects provide hands-on training for the development of future ground and space-based telescope technology.

H. HIGH-QUALITY TRAINING ENVIRONMENT FOR THE NEXT GENERATION OF RESEARCHERS AND RESEARCH LEADERS

Astronomy students require a range of professional and personal skills to successfully conduct and lead research on the international stage. Capitalising on the ASTRO 3D team's existing experience, we run annual workshops in proposal writing skills for scientific publications, telescope and supercomputing proposals, postdoctoral position applications, and ARC grant and fellowship applications.

We provide extensive training in scientific publication writing. We have held 16 Writing Retreats, which help our members develop a collegial network across the Centre, become comfortable in a peer-supported academic writing culture and to share knowledge, practices and experiences related to writing and publishing.

"These retreats are absolutely brilliant for finishing those difficult papers that otherwise would not be written. Best use of my time by far!"

~ Anonymous Writing Workshop participant

Our students and early career researchers organise professional development days in conjunction with our Annual Retreat and Science Meetings. Training has included mental health awareness, presentation skills, developing and maintaining collaborations, scientific leadership, interview skills and CV preparation. Presentation skills workshops provide personalised feedback on slide design, science communication, and body language to develop confidence and skills. Our students and ECRs are encouraged and financially supported to present their research findings at our Science Meetings, and at conferences and workshops.

Junior researchers develop their leadership skills and experience through our leadership workshops and through committee membership across the Centre, including serving on the Executive Management Committee. Junior researchers also serve on the Scientific Organising Committee for national and international meetings for ASTRO 3D.

Our proposal writing programs are run annually and help researchers propose for telescope and supercomputing time. These training programs have been highly successful. PhD student Stephanie Bernard was the first Australian PhD student to be awarded time on a NASA Great Observatory (Spitzer). Our students and ECRs have more than 20 successful proposals as lead investigators on the world's largest optical telescopes (VLT, Keck, Gemini, Magellan)

I. RESEARCH OPPORTUNITIES TO WORK ON LARGE SCALE PROBLEMS OVER LONG PERIODS OF TIME

All of our surveys and projects are large-scale, multi-node, multi-year programs, which are only enabled by long-term investments such as the Centre of Excellence scheme. The MWA Epoch of Reionisation survey is a long-term survey that spans more than a decade. Our ASKAP surveys will take at least five years to conduct. The SAMI survey spanned the first three years of the Centre, with its successor, the Hector survey, operating for the final three years of the Centre. The Galaxy Evolution and First Stars projects are large multi-year programs that utilize multiple different telescopes and facilities. The GALAH survey is a 7-year survey that reached its half-way point in 2020. The Genesis theory program covers the entire seven years of the Centre.

"There's an additional thing about ASTRO 3D that I haven't found elsewhere, it's really that part of the more nurturing aspect. They really empower you to take the lead of things, to really be part of a lot of different projects. They make you feel like you are contributing, more than just your scientific aspect but that you are really contributing to a bigger project. – this is, to me, something I haven't seen in other countries."

ASTRO 3D Fellow, Claudia Lagos
University of Western Australia

J. IMPACT ON THE WIDER COMMUNITY

We impact the wider community through our far-reaching education and outreach programs. Telescopes in Schools targets high school students, began in Victoria and operated by University of Melbourne. This program has been highly successful in encouraging students, particularly girls, into STEM at university. The pilot program, funded by the Laby Foundation, began with low SES schools in Melbourne and surrounds. It produced a 100% increase in girls in year 12 physics.

We have extended this program to 25 schools in regional and remote Western Australia, Northern Territory, South Australia, Tasmania, Victoria and Queensland, reaching nearly 3000 students and an additional 3000 community members. In 2020, we received an $85,000 Federal Government Community STEM Engagement Grant for our the Scientists Taking Astronomy to Regional Schools (STARS) program. In 2021, we will extend our rural program to include indigenous school in collaboration with the Tjabal Indigenous Higher Education Centre. We also operate in Western Australia through the SPIRIT Telescope program, targeting female students in regional WA through remote telescope projects.

ASTRO 3D has partnered with YMCA Space Squad since 2018 to deliver talks to year 6-12 students and help students conduct spectroscopy experiments. We also offer virtual and in-person work experience programs and curriculum-linked Depth Studies for high school HSC students.

"Our students were so impressed and engaged throughout the two very full days and nights of quality teacher and learning experiences. You have helped open their eyes to possible career paths, as well as increase their knowledge of astronomy, astrophysics and engineering."

Participating teacher evaluation

To reach a broader audience, ASTRO 3D received a National Science Week 2019 grant to work collaboratively with choreographers, musicians and

dancers to bring our science to a new audience in a dance production.

We share our discoveries via regular press releases, with accompanying animations, videos and social media, and Monthly Media posts on our website explaining current research. Our members also regularly participate in public outreach events, including AstroFest in Perth, AstroLight Festival in Melbourne, Science in ACTion in Canberra and the Perth Science Festival. ASTRO 3D has its own Facebook page, Twitter account, YouTube channel, Instagram and LinkedIn accounts to share our research findings, content, and videos.

Our Centre encourages industry engagement and collaborations. Genesis team members have close links with national facilities such as the National Computing Infrastructure, and we act in various advisory capacities for the astronomical community and the HPC sector. We coordinated the astronomy stream of the Australasian Leadership in Computing Symposium in November 2019, and we are actively engage with the Department of Industry and Department of Education in funding opportunities to meet the future supercomputing needs of the astronomy and physics community.

Through the Sydney Astrophotonic Instrumentation Laboratory (SAIL) led by CI Joss Bland-Hawthorn and AI Sergio Leon-Saval, we collaborate with other research groups worldwide to develop new materials and devices for astronomical instrumentation and space satellites. Developments include advanced photonics sensors for the farming industry using robotic platforms, a compact solar-powered laser-weeding system to be deployed on farm-robots, and a prototype portable greenhouse spectroscopic sensors for the water industry.

Many of these projects have assisted SAIL's developments in astronomical instrumentation, including the Hector instrument. The SAIL labs are an ideal training ground in prototyping R&D, offering 3-month internships for ASTRO 3D students and ECRs to gain experience in optics and photonics. In 2021, we will run Maker workshops in collaboration with SAIL labs and the ANU Makerspace to develop transferable skills in design thinking, experimentation, prototyping and working with 3D printing technologies.

SkyHopper is a mission concept for an Australian Infrared Cue Satellite led by CI Trenti at University of Melbourne with participation of multiple ASTRO-3D partners, including ANU, Macquarie, Swinburne,U Sydney, UWA, Curtin and Macquarie. An industry-focussed spin-off to SkyHopper has been funded in 2020 by the Australian Space Agency.

Astrophysics PhD students gain significant problem-solving skills, data science expertise, high level programming and statistical skills, providing highly skilled graduates for roles in the broader workforce. Our SciCoder workshops introduce ECRs to modern programming practices, languages and tools to help our researchers write better code, code faster, and leverage more tools and software. We train students to manage big data for careers in population statistics, medical science, bioinformatics, banking, media science and genomics.

We offer communications traineeships to train students and ECRs in science communication, utilising social media platforms and WordPress to publish content. Our students and ECRs attend media training workshops by Science in Public, including Meet the Press training sessions.

"I really enjoy working with students and young postdocs – they are very energetic and it's very satisfying seeing them start with very little knowledge about the project, about the science and building that up over a couple of years, and finally seeing them become masters in a very important area of science. If they don't get other high-profile research jobs, they go into industry and take up usually positions in data science, which is a very important contribution to the community"

ASTRO 3D CI, Lister Staveley-Smith, University of Western Australia

2. ACHIEVEMENTS AND PROGRESS AGAINST CENTRE OBJECTIVES

We are achieving or exceeding our ARC and Centre specific KPIs, as shown in Appendix 1 and our 2020 Annual Report.

3. KEY CHALLENGES AND MITIGATION STRATEGIES

Changing technology: Rapid technological advances have created challenges that are new opportunities. The new task-based hydrodynamics and gravity code SWIFT exploits task-based parallelism designed for many-core compute nodes interacting via MPI using asynchronous communication to improve speed and scaling. We have migrated our Genesis simulation codes to SWIFT, dramatically improving the speed and scalability to many thousands of cores that allow us to tackle much larger problems. This change has significant advantages; we can now track X-ray heating during the epoch of reionisation through a 300 billion particle simulation of a 210 Mpc/h box, as well as tracking the dynamical models of clouds smaller than the Magellanic clouds in the Local Group.

COVID-19: COVID-19 provided challenges and opportunities. Telescope shut-downs delayed our optical telescope programs for Galaxy Evolution and GALAH by several months. Fortunately, both teams

had accumulated a substantial amount of data for their core and ancillary programs to on during this period. The MWA and ASKAP radio telescopes remained operational throughout COVID-19. The lack of travel and visas impacted the ability of our students and postdocs to begin overseas positions. We re-routed our unspent travel funding into a COVID-19 extensions scheme to distribute funds to students and postdocs based on urgency and need. To provide international exposure for our students and ECRs on the job market in 2021, we initiated International ECR Zoom Seminars targeted to the European and US job markets.

Telescope and instrumentation delays: James Webb Space Telescope launch delays, initially scheduled for 2018, impacted the First Galaxies science plan. In line with advice from our International Advisory board, we focused on galaxy candidates discovered in the Hubble Space Telescope BORG survey, and follow-up observations using ground-based telescopes Keck, VLT, ALMA, and Magellan. We also moved investigations on chemical enrichment with JWST sources to Hubble Space Telescope z~1-2 galaxies.

An Anglo-Australian Telescope decision to modify the telescope mounting required the Hector team to redesign the sky fibre, mounting and positioning systems, causing several months delay in addition to Covid-19 hiring delays of international engineers. The Hector survey is now slated for commissioning in mid-2021. Two Hector postdocs are currently working on the survey design and development of Hector. We have delayed the start date of the final two Hector survey postdocs to begin in mid-2021.

Supercomputing processing delays: During 2018-2019, our radio surveys experienced significant delays for data processing on the Pawsey Supercomputer. We used HPC company DownUnder Geosolutions (DUG) to supplement the Pawsey processing of MWA data to mitigate these delays. This combined use of Pawsey and DUG for data calibration and analysis has led to the deepest epoch of reionisation limits using the largest suite of MWA epoch of reionisation data. We are conducting a further exploration of such innovative approaches to our data processing needs.

Taking advantage of new opportunities: Australia became a strategic partner of the European Southern Observatory in 2017. We pivoted to take full advantage of this opportunity, including securing large MUSE, SINFONI, and XSHOOTER programs. We have also engaged with ESO at a high level; our members now serve on the ESO Users Committee, the ESO Telescope Time Allocation Committee , ESO Council. Our members developed the science case for the MCAO assisted visible imager and spectrograph (MAVIS), an Australian-led instrument. for ESO. These efforts strengthen ASTRO 3D science, increase Australia's standing in the European astronomical community, and strengthen Australia's future prospects for full ESO membership.

Over the past few years, Virtual Reality has undergone a revolution in technology and affordability. To take advantage of this opportunity, we transitioned our planetarium production into a virtual reality production, providing greater interactivity and engagement to high school students and the general public. Our Virtual Reality (VR) Program will allow senior high school students to experience the epoch of reionisation and conduct experiments in space utilising interactive wireless Oculus Quest headsets. Science and Education Reference Committees oversee our program to ensure that the VR experience is scientifically accurate and aligned with the Australian Curriculum.

In 2018 and 2019, we operated the Uluru Astronomer in Residence program, where astronomers at Uluru engage with members of the public. After reviewing the partnership, we decided that Indigenous students would be more directly supported by an Indigenous work experience program, in collaboration with schools and State and Federal Government Departments of Education. We have received a $20M Department of Education grant to support this program. We will continue to partner with Voyages by providing our VR program to members of the public at Uluru.

4. CENTRE MANAGEMENT AND STRUCTURE

Leadership Role of Director: Director Lisa Kewley established ASTRO 3D based on her vision and strategic direction, drawing from her experience editing the 2016-2025 Australian Astronomy Decadal Plan. Director Kewley leads the strategic direction of the Centre, including driving the integrated nature of the projects and surveys. She connects our partner organisations and external stakeholders and drives capacity building in our training programs and leadership opportunities for junior researchers. She is an excellent mentor and supervisor for the central management team. She chairs the weekly management team meetings and the monthly Executive Management Committee meetings. She serves as Deputy Chair on the Science Management Committee (chaired by Deputy Director Stuart Wyithe), and is involved in the initiation and start-up of new Centre committees and programs. She was the main driver in bringing on the three new nodes, which was a huge achievement in the difficult financial circumstances of the university sector.

Centre structure: The Centre Structure is shown in Appendix 2. The Executive Management Committee (EMC) comprises the Director, Deputy Director, COO, Business Manager, Node Leaders, Collaboration Leader, and Committee Chairs. Meetings are held monthly with committee chairs (Equity, Diversity and Inclusion, Senior ECR, Junior ECR, Student and Sustainability Committees)

providing reports. The EMC sets the strategic agenda and operations priorities, including budgeting and allocation of Centre funds.

The Science Management Committee (chaired by Deputy Director Stuart Wyithe) is comprised of survey/project leads and key investigators in specific target areas. This committee oversees scientific progress against milestones and identifies risks and new opportunities for the Centre, with reporting to the EMC.

We have combined our National and International Advisory Boards into one Board to provide comprehensive oversight of our scientific, education/outreach, and training programs. The Board meets annually and provides a written report to the Director. The Board, chaired by Prof. Tim de Zeeuw (Leiden) with members Prof. Lars Hernquist (Harvard), Prof. Linda Tacconi (MPE), Prof. Mary Putman (Columbia), CEO Sue Weston (Comcare), and Dr Bobby Cerini (Questacon), has been instrumental in ensuring that the Centre is conducting world-leading science and operating effectively and efficiently.

Administrative, financial and operational arrangements: The Centre administration, based primarily at the Australian National University, and supported by administration staff at the large nodes, provides efficient professional and logistical support for the wide range of Centre activities. To ensure an integrated approach and effective service delivery for the Centre across multiple nodes, we introduced a transparent set of KPI reporting tools, financial expenditure reporting, event management, funding applications and membership database management. Monthly administrative meetings review processes and ensure a cohesive team. The COO works with the Director and Business Manager to review the Budget quarterly, with central and node financial expenditure reconciled quarterly.

The Education, Outreach and Communications program is overseen by the COO and led by the Senior Education, Outreach and Communications (EOC) Officer based at ANU. Each large node has a part-time Education/Outreach Officer dedicated to outreach activities and specific education programs. Monthly EOC meetings ensure the education/outreach programs are meeting their objectives. The COO and the ANU Administrative Officer also manage the external and internal communications.

Intellectual property management: ASTRO 3D adheres to the IP requirements of each partner university, guided by the ARC "National Principles of Intellectual Property Management for Publicly Funded Research". In 2021, we expect our first major commercialisation project - our Virtual Reality app created in conjunction with Deakin University. The University of Sydney IP office manages developments of the SAIL group.

Attracting high-quality staff and students: ASTRO 3D attracts high-quality, diverse researchers, professional staff and students from around Australia and internationally. We have developed best-practice hiring guidelines through our Equity, Diversity, and Inclusion (EDI) committee, which also created best-practice Event Guidelines to ensure that ASTRO 3D organised or sponsored events are inclusive and equitable. Our EOC staff and trainees develop skills and experience for career advancement in science communication through our first-class education and outreach programs. Our professional staff access training, mentoring, and leadership programs and are engaged in best practice in KPI and financial expenditure reporting.

An evolving workforce (succession planning): The Centre succession planning has been incorporated since its inception. Postdoctoral researcher positions are predominantly Level A in Year 1, increasing to Level B and C positions in Years 3-7, ensuring a clear career progression for the best young researchers. Our Fellowship program includes high-performance postdoctoral Fellowship extensions (1 FTE at each node during Years 6-7) to extend the tenure of highly performing junior research staff, providing the best career opportunities for our most successful researchers. All Project/Survey leaders and Node leaders are supported by junior science leader deputies who are trained to take over as Leaders under our succession planning strategy. This succession has already begun, with Barbara Catinella replacing Lister Staveley-Smith as Node Leader at UWA and Emma Ryan-Weber replacing Karl Glazebrook as Node Leader at Swinburne. Similar progressions are planned at other nodes. Our female-only continuing positions at UWA, Melbourne, ANU, and Sydney ensure a career path to permanent positions for women, which have been historically under-represented in the senior levels of astronomy.

APPENDIX 1 - 2020 KPIs

PERFOMANCE MEASURE		2017 ACTUAL	2018 ACTUAL	2019 ACTUAL	2020 TARGET	2020 ACTUAL
Number of research outputs	Papers in refereed journals	11	110	213	*100*	**227**
	Media releases	1	5	7	*6*	**11**
	Centre Videos	-	-	15	*12*	**64**
	Facebook Page posts	-	-	73	*26*	**71**
	Twitter posts	-	-	228	*52*	**119**
	Exhibition or performance	-	-	3	*1*	**2**
	STEM Education workshops	-	-	6	*6*	**5**
	Website News Updates	-	-	7	*12*	**21**
	VR Program Development	-	-	1	*1*	**1**
Quality of research outputs	% of refereed papers in journals with impact factor > 2.5	100%	100%	100%	*80%*	**100%**
Number of training courses held/offered by the Centre	Professional skills workshop	1	4	2	*1*	**1**
	ECR training day	1	1	2	*1*	**1**
	Writing workshops	2	5	6	*6*	**3**
	Transferrable Skills workshop	-	-	1	*1*	**3**
Number of workshops/ conferences held/ offered by the Centre	International conference	0	2	2	*2*	**2**
	National conference/ workshop	1	2	2	*2*	**2**
Number of *additional* researchers working on Centre research	Postdoctoral researchers	16	14	3	*10*	**8**
	Honours students	2	1	3	*2*	**5**
	Masters by coursework	0	2	3	*2*	**0**
	PhD students	28	13	20	*12*	**15**
Number of presentations/ briefings	Public briefings/lectures	3	123	230	*40*	**246**
	Government briefings	5	22	29	*4*	**35**
	Industry briefings	0	12	39	*2*	**42**
	Non-government organisation briefings	0	5	6	*6*	**7**
	Briefings to professional organisations & bodies	4	36	6	*4*	**6**
	Professional conferences/ workshops presentations	68	163	123	*40*	**221**
Number of new organisations collaborating with, or involved in, the Centre	New collaborative relationships	5	7	15	*4*	**11**
	New participating organisation	-	-	0	*1*	**3**

Continued

PERFOMANCE MEASURE		2017 ACTUAL	2018 ACTUAL	2019 ACTUAL	2020 TARGET	2020 ACTUAL
Maintain a collaborative and cohesive structure	Cross-node first authorship of publications	36%	46%	39%	*85%*	**37%**
	Project team meetings with cross-node collaboration	4	12	6	*6*	**6 cross-node teams that meet at least monthly**
	Centre-wide climate survey	0	1	0	*1*	**0 (to occur in 2021)**
Create a diverse Centre	Females at all levels	37.7%	38.2%	38.7%	*45%*	**42.5% (April 2021 44.9)%**
	At least 35% travel funds to females	28%	42%	42%	*45%*	**51%**
	Female visitors	44%	50%	58%	*50%*	**n/a (COVID-19)**
	Child care at all Centre-suported conferences	100%	100%	100%	*100%*	**n/a (COVID-19)**
Build the expertise for the next-generation telescopes	Students working on optical GMT pathfinder instruments	13%	29%	25%	*20%*	**37%**
	Students working on radio SKA pathfinder instruments	10%	16%	31%	*20%*	**20%**
	Students working on space telescope data	13%	16%	6%	*10%*	**15%**
	Students with data intensive research experience	19%	80%	51%	*30%*	**44%**
Train the next generation of scientists	% satisfaction with Centre-run skills workshops	-	-	87%	*80%*	**87%**
	% of PhD students and ECRs attending skills workshops	-	-	31%	*20%*	**30%**
	% ECRs achieving prestigious fellowships	-	-	28%	*20%*	**27%**
	% PhD students or ECRs achieving high quality jobs in other fields	-	-	28%	*20%*	**24%**

APPENDIX 2 - 2021 ORGANISATION CHART