Theoretical Astrophysics in Australia

Submission to Decadal Plan Working Group 3.1

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Introduction

In this document, we identify the value of theoretical and computational astrophysics to the astronomy community generally and to the aims of the Decadal Plan. We also present our vision for the future. In particular, we point out:

- The central role played by **individual researchers** in delivering the theoretical infrastructure to support Australian astronomy.
- The need for a specific plan to increase the number and diversity (whilst maintaining the quality) of personnel with expertise in theoretical astrophysics who are employed in National Facilities, universities, and Centres of Excellence (CoEs).
- The need to incorporate theoretical infrastructure into every stage of the life cycle of a National Facility: setting science goals, selecting and designing instruments, handling and interpreting scientific data.
- The need to provide nationally competitive supercomputing facilities, network infrastructure, and local CPU and storage resources to support theoretical work based on large-scale computations.
- The value of the Australian National Institute for Theoretical Astrophysics (ANITA) as a high-level organizational structure for some of these initiatives.
- The value of ANITA in continuing to develop astronomy within Australia as a coherent, rigorous academic discipline and educational pathway for attracting young people into science and engineering, e.g. by organizing postgraduate winter schools and training mediated by facilities such as the Access Grid.

People

Advances in theoretical astrophysics (and physics generally) underpin the discipline of astronomy as a whole. The symbiosis between experimental and theoretical science is typical of all scientific disciplines – with each branch informing and stimulating the other. Australian astronomy therefore needs a strong theoretical infrastructure to remain vital and robust. This infrastructure is mainly composed of people. The need for human infrastructure has already been recognized, with a number of new tenured appointments in theoretical astrophysics being made in university departments over the last five years.[1] It is essential that this pattern be maintained. We also recommend that it be enhanced in the following ways.

[1] Asplund, Sutherland (RSAA); Donea (Monash); Cairns, Kuncic, Lewis, Wheatland (Sydney); Melatos, Wyithe (Melbourne); Gibson, Maddison (Swinburne); Wardle (Macquarie).

1. ***Institutional diversification.*** At the present time, our theoretical infrastructure resides almost entirely in university departments (physics, astronomy, and mathematics). Whilst this is natural to some degree, some diversification will become necessary in the next decade. University appointments should be supplemented with appointments in National Facilities and Centres of Excellence (combining observational, theoretical, and computational astrophysics) to maximize the scientific impact of the next generation of National Facilities. This is discussed further below.

2. ***New positions and critical mass.*** It is possible that opportunities will arise to create new positions in universities over the next decade, driven by demand from foreign students, for example. Such opportunities might flow from a broad national initiative to boost the number of research-intensive academics, as occurred recently in Canada, or from individual institutions wishing to boost their representation in astronomy, a subject that is a proven draw card with students. In such a climate of increased resources, careful thought should be given to building theoretical groups with critical mass.

3. ***Career structure.*** At the present time, most theoretical and computational astrophysicists (and indeed most observational astrophysicists) operate within the standard 'career pyramid', progressing from student to postdoctoral research associate to fixed term research or lecturing appointments to tenured academic (with substantial attrition at each stage). This structure meets some – but not all – of the needs of the Australian astronomy community, especially in view of the long-term nature of the planned investment in new National Facilities. An issue in this regard is the special position of *code-developers* – people who engage in the time-consuming and challenging task of writing general-purpose computer simulations, which are subsequently used by hundreds of people to model basic physical processes, motivate the design of new observational facilities, and interpret the data from facilities. Code-developers are the theory analogue of *instrument-builders*. Both groups are somewhat underappreciated in academe, because the painstaking and long-term nature of their work harms their rate of publication. Nevertheless, they are absolutely vital to the astronomical enterprise. We recommend that alternative career structures be developed for these groups, e.g. within National Facilities, or through multi-stage, long-term postdoctoral schemes where publication rate is not the only selection criterion.

Integrating Theory into National Facilities

Theory will be integrated deeply into every stage of the life cycle of the next generation of major observational facilities – the telescopes themselves and the instruments they host. Before construction, theory inspires the science drivers and design – what do we really need to build, and with what specifications (given theoretical predictions of what one will see)? How should the science case be localized to the Australian context? After construction, theorists maximize the scientific impact of the facility – by interpreting and synthesizing the enormous amounts of data it produces, and by fertilizing the next round of "big" theoretical ideas. Internationally, this symbiosis is well established (e.g. in missions like NGST, Chandra, and WMAP, and in facility-related science institutes like STScI) and is inevitable in large ($10M+) projects.

We recommend that a specific plan be developed to resource the integration of theoretical and computational infrastructure into National Facilities. Such integration cannot be sustained solely on the back of ARC grant funding to theoretical and computational astrophysicists in universities. At the present time, approximately $1M per annum in ARC DP funding (including fellowships) comes to astronomy, and there is the possibility of securing a similar additional amount through a Centre of Excellence. Even in an extreme scenario where these resources are devoted entirely to scientific (including theoretical and computational) support of National Facilities, they are insufficient (as a percentage of the capital and operating costs of a $100M-class facility) to ensure that the scientific impact of the Facilities is maximized (at least, that part of the impact which is identifiably Australian).

Two types of resources are needed to implement this plan. Before construction, the main requirement is for (modest) project-specific funding to support theoretical and computational modeling of the science goals and to feed scientific input into the engineering design of the National Facility. After construction, the main requirement is for a sensible fraction of the science component of the facility/instrument operating budget to be devoted to relevant theoretical work. For example, the ATNF and AAO currently employ staff scientists (approximately 10-15% of facility staff) who fulfill dual functional and research roles. We recommend that these dual-role positions be opened to applicants with theoretical and computational expertise as well, and that such applicants are proactively encouraged to apply, in line with international practice (e.g. STScI). Examples of functional roles ideally suited to such applicants include developing data processing pipelines, algorithms, and Virtual Observatory infrastructure, simulating the observational parameter space (and hence influencing the design) of new facilities, and participating in policy development and facility management.

Similarly, we recommend that a balanced fraction of the postdoctoral positions in National Facilities (e.g. Bolton and other fellowships) should be opened to theoretical/ computational applicants whose research interests are compatible with the Facility. Again, such positions would include a functional component where appropriate.

Below we summarize some of the key **scientific opportunities** available to the National Facilities planned for the next decade. To help exploit them fully, we match each of these opportunities with Australian institutions that currently provide **theoretical infrastructure** in that area.

Radio: Square Kilometer Array, Extended New Technology Demonstrator, Low Frequency Demonstrator

1. Structure of the Universe at the epoch of reionization – formation of the first stars (Melbourne, Swinburne)
2. Origin and dynamics of magnetic fields in the Galactic interstellar medium, including new techniques for scintillation imaging (Sydney, Macquarie)
3. Energy generation by compact objects – radiation and outflows from black holes and neutron stars (Sydney, Melbourne, RSAA, Monash)
4. Cosmological distribution of neutral hydrogen – evolution of structure, star formation, and the dark energy equation of state (UNSW, Swinburne)

Optical/Infrared: Extremely Large Telescope, Antarcticic Astronomy

1. Formation of extrasolar planets in disks around young stars (Monash, Swinburne, RSAA)
2. Distribution of matter and energy in the Universe – theoretical analysis of data from future wide-field redshift surveys, the successors of 2dF and 6dF (UNSW, Sydney, Swinburne, RSAA, Melbourne)
3. Symbiosis between supermassive black holes, galaxy formation, and galactic activity (RSAA, Melbourne, Sydney)

Millimeter: Australia Telescope Compact Array Upgrade

1. Formation of stars, especially high-mass stars, in the turbulent, magnetized interstellar medium (Macquarie, Swinburne)
2. Galactic archaeology – the history of the chemical elements in the galaxy (RSAA, Swinburne, Monash)

Gravitational waves: Australian Consortium for Interferometric Gravitational Wave Astronomy, Pulsar Timing Array

1. Gravity waves from accreting neutron stars and merging neutron stars – a new non-electromagnetic window on the Universe (ANU, Monash, Melbourne)
2. Gravity waves from merging galaxies in the early Universe (Melbourne)
3. Tests of strong-field gravity (ANU, Monash, Melbourne)

High-energy particles: CANGAROO

1. Origin and composition of the highest-energy cosmic rays (Adelaide, Monash, Melbourne)
2. High-energy radiation from neutron stars and supernova remnants (Sydney, Melbourne)
3. Particle (e.g. neutrino) astrophysics (Adelaide, Melbourne)
4. High energy radiation from blazers (Adeldaide, RSAA)

Computational Resources

Approximately 50% of theoretical astrophysics research in Australia utilizes advanced computation on state of the art computational facilities. It is fortunate that these facilities can be easily centralized and shared across a wide range of sciences, so that the initial capital cost and subsequent upgrades, maintenance, and depreciation are spread over a diverse range of scientific programs. The welcome and far-sighted establishment of centres such as the Australian Partnership for Advanced Computation (APAC), the Sydney–based Australian Centre for Advanced Computing and Communications (AC3), and the Victorian Partnership in Advanced Computation (VPAC) testifies to the fact that this type of activity cannot be supported on a stand-alone basis by every University; when supercomputing was introduced into Australia in the mid 1980’s, it was quickly realized that a national facility model would be effective. It is therefore essential that the existing supercomputing centres be maintained and expanded, together with the software and maintenance infrastructure needed to support computational astrophysics in particular.

An essential element of the above model is the provision of high-bandwidth connectivity to all academic users. This will assume even greater importance shortly, when grid computing and Access Grid communications become common.

At the same time, advanced computation requires significant local facilities in the form of multi-terabyte storage and CPU capability for the post-processing of output, for special-purpose experiments, and for student training. There are numerous examples where these activities, especially student training, have subsequently led to applications in other technological areas. For these reasons, the development of computational infrastructure within universities should be encouraged.

The international trend towards publishing software for, and output from, theoretical simulations on-line, in parallel with the on-line publication of observational data, opens up new opportunities concerning how computational astrophysics will be done in the future. We recommend that sufficient resources be allocated (through the usual funding channels, e.g. LIEF) to the development of the theory component of the Australian Virtual Observatory (AVO), e.g. standardizing and documenting simulation software for publication, compiling standard dictionaries of content descriptors, and designing portals to facilitate running the software on the grid and combining its output with observational data in the VO.

ANITA

The mission of ANITA is to:

1. Develop the Australian theoretical and computational astrophysics community by facilitating communication and collaboration between theorists and providing a focus for the community;
2. Raise the national and international profile of theoretical astrophysics;
3. Promote links with the national astronomical community by assisting in the theoretical interpretation of observations, motivating new observational programmes and increasing the scientific return from national investment in observational infrastructure.

ANITA currently consists of 39 academic/professional staff, 23 student members and is operated by a steering committee consisting of a convenor, an immediate past convenor, seven steering committee members including a student member and *ex officio* the president of the ASA. ANITA has a good relationship with the ASA; the convenor has been invited to serve on ASA council. ANITA formally commenced in October 2003 but had been active for about a year previously. Full details of ANITA's activities may be found at the website www.anita.edu.au.

ANITA provides a ready-made organizational structure to coordinate efficiently many of the activities discussed above. For example, ANITA supplies representatives to working groups that form to plan new observational facilities (telescopes and instruments). ANITA can also help to coordinate the involvement of theoretical and computational groups in Centres of Excellence and related initiatives. And ANITA is well placed to represent the interests of the community in devising a national strategy for the development of computational (supercomputing and networking) infrastructure through APAC, VPAC, and university facilities, as well as devising a national strategy for the theoretical and observational components of the Virtual Observatory.

We propose that a mechanism be identified to gain some operational funding for ANITA in the short term. The main use of this funding will be to support the highly successful program of workshops and conferences organized with minimal resources by ANITA since its inception.[2] Excitingly, these workshops have been attended by a wide cross-section of the Australian astronomical community, including observational astronomers and PhD students. They are becoming an important community resource. With increased funding, ANITA would be able, for example, to subsidize student attendance and invite international researchers to give keynote talks. The required amount of funding is modest, approximately $20k per annum.

ANITA and Graduate Education

Separately, we recommend that funding be secured to design and then run an annual series of graduate lecture courses in astrophysics, delivered partly via the Access Grid but also through a two-week residential workshop analogous to the Harley Wood Winter School. ANITA is prepared to coordinate such a lecture series. It is important that Australian graduate students in astronomy are well trained in the foundations of their discipline. Training opportunities are currently provided in observational techniques (e.g. ATNF Synthesis Workshop); the ANITA lectures would provide an analogous training opportunity in the fundamentals of astrophysics, which do not receive uniform coverage in the curricula of all Australian universities at the present time. Leading scientists from Australian institutions would offer the courses, supplemented by international lecturers if funding permits. The scale of funding required is estimated at approximately $100k to establish the programme and produce teaching materials, followed by annual operating costs of $50k, funded perhaps from an endowment or long-term grant.

General comments

1. We emphasize that the interpretation of data should not be seen as the *only* role of theory, although all good theoretical work is ultimately inspired by the richness of the observed sky. Aspects of astrophysical theory that may not be amenable to immediate observational tests are nonetheless crucial to our understanding of astrophysical processes.

2. Theorists are responsible for the development of new techniques that have a wide-ranging impact on astronomy. Australian examples include the theory of thermal and nonthermal emission from astrophysical plasmas and the computational technique Smoothed Particle Hydrodynamics (SPH). The latter is a good example of an industrial linkage – SPH is used in the movie industry for the realistic generation of sequences of moving gases and fluids.

3. New major observational projects (say equivalent in scope to the 2dF project) should factor in budgetary support for theoreticians and should involve theoreticians in the planning stages. This would maximize the scientific payoff to the Australian community from key observational projects.

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[2] Stellar Astrophysics (Swin, 2005), Computational Astrophysics (ATNF, 2005), High-Energy Astrophysics (RSAA, 2004), Gravity (USyd, 2004), 2nd ANITA Workshop (Macq, 2003), Galactic Cehmodynamics (Swin, 2003), Theoretical Astrophysics and the VO (USyd, 2003), AGN and Starbursts – Charlene Heisler (RSAA, 2002), Nuclear Astrophysics with the Murchison Meteorite (Monash, 2002), 1st ANITA Workshop (Monash, 2002).

4. Many theoreticians and observers participate in scientific projects involving overseas–based facilities such as the Chandra X–ray Observatory. A fund should be established to support aspects of this activity that are not covered by the ANSTO Large Facilities Fund and to educate other Australian astronomers in the utilization of such international facilities.

5. As a result of the ARC funding program for Centres of Excellence, it is expected that both theorists and observers will seize the opportunity to formulate competitive bids for such centres. The theoretical community is encouraged to take advantage of these opportunities and to formulate internationally competitive and widely-inclusive proposals.

6. There is strong interest in some quarters for the creation of a theoretical institute with a mandate to take a leading national role, similar in some respects to the role of our national observational facilities. This would involve a large amount of lobbying of state and federal governments and Universities and would require a dedicated individual or group of individuals to lead such an initiative. Whilst there is no current proposal for such a centre, we do not rule it out as a possibility within the next ten years.

7. The main tradition of Australian astronomical observational research is in radio and optical astronomy. However, both theoreticians and observers realize that qualitatively different information comes from areas such as X–ray and gamma–ray astronomy – true multi-wavelength research must embrace these parts of the electromagnetic spectrum as well. In many cases, theoreticians lead new research in these fields, developing important linkages for the whole community.

Appendix A: Summary of theoretical and computational research projects and infrastructure in Australian astronomy

Field(s)	Institution(s)
Solar and Space Physics (Solar seismology, solar and planetary radio emission, solar radio bursts and flares, auroras)	Sydney, Monash
Plasma astrophysics (Plasma emission, absorption and transfer processes, particle acceleration)	Sydney
Planetary Science	ANU, Monash, Swinburne
Stellar structure and evolution; effects of environment on nuclear fusion	ANU, Monash, UNSW
Star formation	Macquarie, NSW
Interstellar medium (HII regions, Galactic Centre, scintillation, molecular shock waves, photodissociation regions)	ANU, UNSW, Sydney
Astrobiology	Macquarie, UNSW
Compact objects (neutron stars, pulsars, relativistic pulsar winds, accretion disk-magnetosphere interaction)	ANU, Melbourne, Sydney
Extragalactic astronomy (galaxy formation and evolution, active galactic nuclei)	Adelaide, ANU, Monash, UNSW, Swinburne, Sydney, Melbourne
Cosmology (big bang, microwave background, dark matter, dark energy, epoch of reionisation, variation of fundamental constants, Lyman alpha forest)	ANU, Melbourne, UNSW
General relativity (classical and quantum)	ANU, Monash, UNSW
Gravitational lensing (mass models of lensing galaxies, cosmological and statistical lensing, quasar structure)	Melbourne, Sydney
Gravitational waves and their detection	ANU, Melbourne, UNSW
Computational astrophysics	ANU, Macquarie, Monash, UNSW, Swinburne, Sydney

In many of the above areas of activity listed in the above table, theorists have collaborated with observers, adding value to the substantial observational programs carried out using Australian national and university facilities. Other theoretical research contributes to the design of new facilities such as the Square Kilometer Array.

Appendix B: Summary of international projects involving Australian theoreticians

Project	Australian Institutions	International Institutions
CANGAROO Gamma-Ray Observatory	Adelaide, ANU, Sydney	Univ. of Tokyo led consortium of Japanese universities
Hadronic models of active galactic nuclei	Adelaide	Max Planck Institut fuer Radioastronomie, Bonn
Project LUNASKA: UHE neutrino astrophysics with the SKA	Adelaide, ATNF	Univ. of Delaware, University of Santiago de Compostela
Gravitational Wave Detection	Adelaide, ANU, UWA, Monash, Edith Cowan Univ, CSIRO	LIGO (US project), GEO (UK/German project), TAMA (Japanese project)
High energy astrophysics of Active Galaxies	ANU, Sydney	Landessternwarte & Max Planck Institut fuer Astrophysik, Heidelberg, University College, London; Consortium of US astronomers using the Chandra X-ray Observatory
Starburst Galaxies and Galactic Centre	ANU, AAO	Berkeley, Univ. of Maryland, Caltech, Oxford
Epoch of Galaxy Formation	ANU	Berkeley and U. Wisconsin, Royal Obs. Edinburgh
Three Dimensional Stellar Convection	ANU	Michigan State Univ. and Univ. of Copenhagen
Models of Mira Variable Stars	ANU	Univ. of Heidelberg
Laboratory Cosmology	ANU	Victoria Univ. of Wellington, Max-Planck-Institut für Quantenoptik
Supernova remnant masers	Macquarie	Northwestern University, Illinois
Epoch of reionisation	Melbourne	CfA Harvard; Princeton
Neutron star accretion	Melbourne	MIT; Canadian Institute for Theoretical Astrophysics
Relativistic pulsar winds	Melbourne	Univ. of Oslo
Solar Active Region Seismology	Monash	Colorado Research Associates, GONG
Solar Tachocline Instabilities	Monash	High Altitude Observatory, Colorado
Evolution of Stellar Populations	Monash	IoA, Cambridge
SPH and MHD	Monash	IoA, Cambridge
Blue Straggler Production in Open Clusters	Monash	IoA, Cambridge and U. Utrecht
Planetary Disruption in Star Clusters	Monash	American Museum of Natural History, IoA Cambridge
Stability and evolution of	Monash	University of California, Santa Cruz

planetary cores		
Evolution of neutron star binaries	Monash	Oxford
Stability of small-N systems in star clusters	Monash	IoA, Cambridge
Interactions between VLBI jets and the surrounding medium	Monash, Adelaide	Astronomical Institute of the Romanian Academy; University College Cork, Ireland
The effects of voids of primordial origins	NSW	Sussex, Oxford
Formation of the Milky Way	NSW	Tohoku University
Origin of post-starburst galaxies	NSW	Tohoku University
Ultra Compact Dwarf galaxy formation	NSW	U. of Bonn, Space Telescope Science Institute; Univ. of Calif.; Bristol U.; Nottingham Univ.
Cosmological variation of fundamental constants	NSW	Imperial College; Cambridge; UC San Diego; UC Lick Obs.; Penn. State; Novosibirsk
Thick disk sub-structure & halo kinematics	Swinburne	Tuorla Observatory, Finland
Effects of environment on nuclear fusion	NSW	Princeton; Michigan State U.
Galactic Streams	Sydney, Swinburne	Strassbourg Observatory, France; Cambridge University
Cosmological simulations/ SKA	Swinburne, Sydney	Arizona State; Durham University; Univ. of Victoria, BC; Univ. of Washington
Galactic Chemical Evolution	Monash	St Mary's College, Canada Rome Obs.
Accretion onto Magnetised Stars	Sydney, Swinburne	St Andrews, UK
Warped CV Disks	Swinburne	Open University, UK
Building Planets with Dusty Gas	Swinburne	Canadian Institute for Theoretical Astrophysics, Universite de Lyon
Synthetic IR Images of Protostars	Swinburne	Universite de Grenoble
Planets in Binary Systems	Swinburne	Potsdam, Germany
Dusty Debris Disks	Swinburne	Princeton and CfA, USA
Solar system radio bursts	Sydney	UC Berkeley
Sub-mm cosmology	Sydney	Caltech
Gravitational lensing	Sydney, Melbourne	MIT, Heidelberg, NRAO
Giant pulses from pulsars	Sydney	Stanford
Pulsar polarisation	Sydney	Jodrell Bank; GMRT
Interstellar scintillation	Sydney	UCSD; Palermo Univ.; Kapteyn Institute; NAO, Beijing
Pulsar spectra	Sydney	Oberling College, Yamagata U.

Energy balance of the solar corona	Sydney	U. New Hampshire
Solar neutrino time-series analysis	Sydney	Stanford
Magnetic reconnection & solar flare statistics	Sydney	U. Waikato