Decadal Plan Mid-Term Review Topic Summary Document: Theory

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Overview

The Australian theory community is a broad and diverse one, pursuing a comprehensive research programme that addresses each of the 6 key questions set out in the Decadal Plan (DP). Australian theorists work on a range of topics that include **gravitational waves** and **cosmology**; **planet, star, and galaxy formation**; **dynamical modelling of star clusters**; theoretical **stellar astrophysics**; **galactic archaeology**; and the development and application of **numerical algorithms and statistical tools for complex astronomical datasets**.

Significant theory activity is undertaken in (at least) 13 universities and institutes; ANU, ICRAR (Curtin & UWA), Macquarie, Monash, Swinburne, U Melbourne, UNSW and UNSW-Canberra, U Queensland, U Sydney, U Tasmania, and UWA. Two ARC Centres of Excellence, ASTRO 3D and OzGrav, play an important role in promoting and sustaining collaborations between groups at several of these institutions, while many groups also have close ties with, or are embedded within, large international projects (e.g. LIGO, the EAGLE cosmological simulations). A defining feature of the theory research programme is the central role played by **high performance computing** (HPC); facilities such as the National Computing Infrastructure (NCI), Pawsey Centre for Supercomputing, and OzSTAR, are a **fundamental component of the theory community's research activities**, and the community's success links intimately to ongoing investment in world-class HPC facilities and related services.

The following summarises briefly theory activities addressing each of the 6 key questions in the DP; assessment of progress so far, and identification of new opportunities; and risks to future progress.

Alignment of Research Programme with Decadal Plan

Q1: How did the first stars and galaxies transform the Universe?

Activity in this area encompasses astrophysical simulations/models and development of statistical tools to mine observational data. Numerical models of atmospheres and elemental yields of zero- and low-metallicity stars provide important insights into early chemical enrichment, with implications for galactic archaeology and observable signatures of the most metal poor stars (ANU, Monash). The formation of the first stars and galaxies are explored with both semi-analytical models (Swinburne, U Melbourne) and hydrodynamical simulations (ANU), and the onset and evolution of the Epoch of Reionization is studied with radiative transfer calculations (Swinburne, U Melbourne). Direct star cluster models connect the formation of globular clusters in the early Universe to the present day (Swinburne, U Queensland), and allow the origin of multiple stellar populations to be investigated. Statistical tools (e.g. CHIPS) are developed to extract information from measurements of 21cm HI emission with low-frequency radio telescopes, such as the Murchison Widefield Array (ICRAR/Curtin).

Q2: What is the nature of dark matter and dark energy?

Activity in this area spans N-body and galaxy formation simulations of cosmological structure formation in non-standard dark matter/dark energy and modified gravity models (ICRAR/UWA, U Queensland, U Sydney); development of observational tests based on e.g. gravitational lensing, microlensing, satellite dynamics, that can be used to discriminate between different dark matter, dark energy, and modified gravity models (ICRAR/UWA, Swinburne, U Queensland, U Sydney); and generation and analysis of synthetic datasets to support the planning and interpretation of observational surveys (ICRAR/UWA, Swinburne, U Queensland, U Sydney).

Q3: How do galaxies form and evolve across time?

This area is significant for the depth and breadth of activities. Stellar evolution models provide crucial predictions for chemical enrichment and dust formation (Monash), and they have fundamental implications for the spectral energy distributions (SED) of stellar populations, which are calculated using state-of-the-art models, such as MagPhys and Prospect (ANU, ICRAR/UWA). Modelling stellar explosions provide insights into the properties of the seeds of present-day super-massive black holes (Monash), and supernovae simulations are crucial for understanding the production rate of heavy elements as well as the rate at which transients occur (ANU, UNSW-Canberra). Galaxy formation modellers have developed cutting-edge, open source, semi-analytical models that are coupled to large cosmological N-body simulations and are used to predict properties of the galaxy population over cosmic time (ICRAR/UWA, Swinburne, U Melbourne). Galaxy formation simulators develop new physical models (e.g. stellar and AGN feedback, chemical evolution) and explore their consequences in hydrodynamical simulations (ANU, ICRAR/UWA, U Tasmania). Several theorists have important roles within large international projects (e.g. the EAGLE and Illustris Simulations). Predictions from these simulations/models are transformed into synthetic observational datasets, incorporating e.g. realistic galaxy SEDs, to support both large galaxy surveys (e.g. Theoretical Astrophysics Observatory) and resolved measurements of individual galaxies (ANU, ICRAR/UWA, Swinburne). Direct star cluster models give important insights into how globular clusters evolve dynamically over cosmic time (Swinburne, U Queensland), and provide estimates of merger rates of neutron stars and stellar mass black hole in dense environments, which are crucial for the study of gravitational waves (Monash).

Q4: How do stars and planets form?
Activity in this area - at ANU, Monash, and Swinburne - spans numerical simulations focussed on theoretical problems (e.g. hydro-dynamical simulations of the first stars, magneto-hydrodynamical simulations of dusty proto-stellar discs) and modelling of observational data, from e.g. ALMA and ATCA (e.g. simulating dusty gaseous proto-planetary discs, planet formation in warped proto-planetary discs). Signatures of newborn planets around very young stars shows that planet formation occurs rapidly; this has motivated new simulations of star formation process that can link star and planet formation, and requires new mathematical understanding of the accretion process (Monash).

Q5: How are elements produced through stars and recycled through galaxies?
Stellar evolution modellers track chemical evolution in low- and intermediate mass stars, and core collapse and thermonuclear supernovae to understand the origin of the heavy elements (Monash, UNSW-Canberra). Binary evolution is likely to make an important but uncertain contribution (e.g. binary neutron stars produce the heaviest elements, such as uranium, but their rates are uncertain); hydro-dynamical simulations are used to study binary interactions (Macquarie), while population synthesis models improve estimates of the rates of mergers (UNSW-Canberra). Hydrodynamical galaxy formation simulations utilise stellar evolution models to explore chemical enrichment of the inter-stellar and circum-galactic media of galaxies (ANU, ICRAR/UWA).

Q6: What is the nature of matter and gravity at extreme densities?
Computationally intensive stellar evolution calculations are used to study matter at extreme densities, including the birth properties of neutron stars and black holes, and equation of state of neutron stars as probed by accretion-powered bursts and glitches (Monash, U Melbourne). A number of groups develop algorithms to identify the occurrence, and invert the physical properties, of gravitational wave sources (Monash, U Melbourne, UWA).

Assessment of Progress against Decadal Plan & New Opportunities
Progress is on track. Of particular note are the mature and sustained collaborations between teams of theorists, and theorists and observers, many of which are facilitated by the ARC Centres of Excellence, ASTRO 3D and OzGrav. This aligns well with an aspiration of the DP: "…the astronomical community should work to increase linkages between the theoretical and observational communities on projects of common interest...". Notably, however, it is vital that the needs of the **rapidly growing gravitational wave and multi-messenger astronomy community are incorporated into the DP**; the first detection occurred months after the 2016-25 DP's release, and the community has grown to ~150 in ~3 years!

Moving forward, it is important that the tools and community expertise are in place to facilitate exploitation of large datasets, and to maximise scientific returns; this is the most significant risk to progress. A consistent message from the Australian theory community is the need for **regular, ongoing investment in world-class astronomy-dedicated HPC access – ~300M CPU hrs annually on an internationally competitive Tier-0 facility;** this could be achieved by joining the EU PRACE scheme, or major upgrades to existing national facilities. Investment should also go into securing continuous access cloud computing (~5k VCPUs), crucial for Bayesian inference and parameter estimation, and ring-fencing OzSTAR as Australian astronomy's Tier-1 facility with regular 3-5 year upgrades. Another consistent message is that a **well-resourced and sustainable Astronomical Data and Computing Service** (ADACS) is also essential to provide **crucial specialist expertise** to develop new algorithms and software. As stressed in the DP, this opens up "...strategies to support career paths for theoretical astronomers whose research programs are not tied to specific observational infrastructure or programs." (p49).