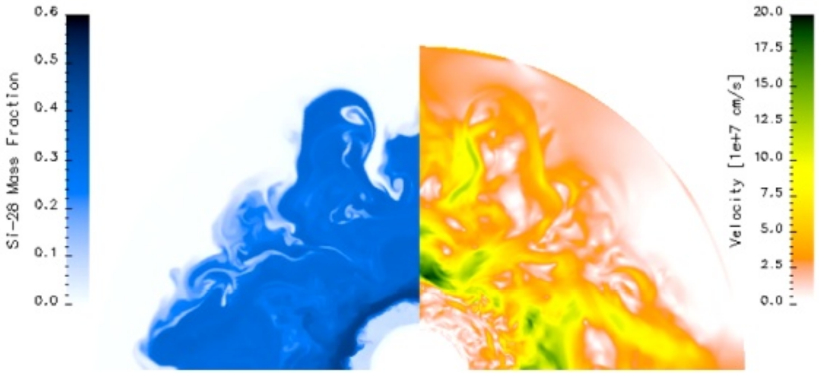
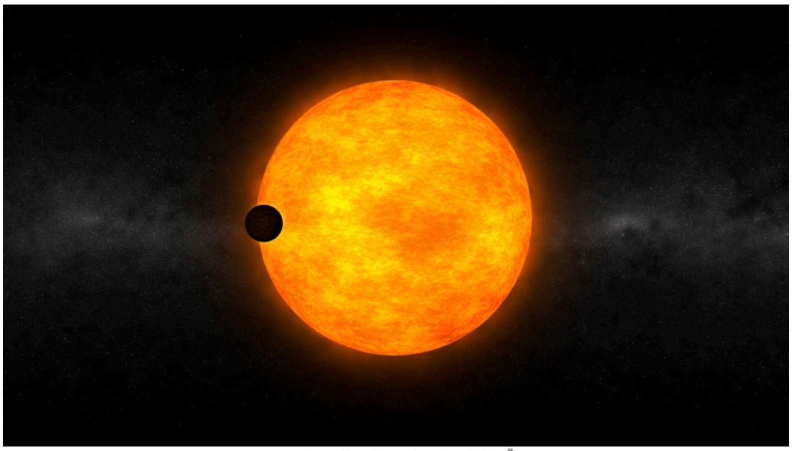
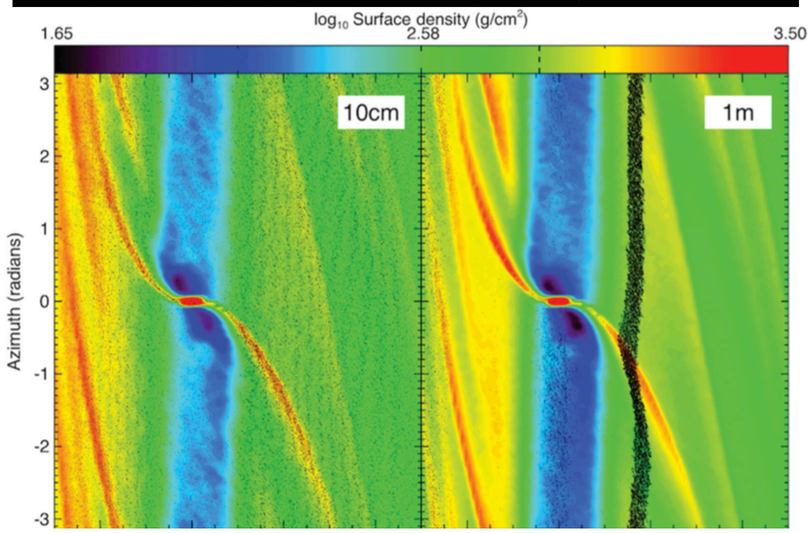
Stars and Planets

Report to the National Committee for Astronomy for the Australian Astronomy Decadal Plan 2016-2025 by Working Group 1.2 August 2014







Executive Summary
The coming decade will be transformative for "Star and Planet" research worldwide. Gaia will increase the number of stars with accurate parallaxes *one-thousand fold*, and will astrometrically detect a new population of planets, complementing the radial velocity, transit and direct imaging discoveries of exoplanets that will continue apace. ALMA will deliver new capabilities in both angular resolution and wavelength parameter space, delivering a *one-thousand fold* increase in performance over previous arrays[1]. In the process it will create the first images of stellar birth *and* the cradles of planet formation. Australia will play an essential role in providing data sets underpinning these advances including all-sky spectroscopic and photometric data essential for the interpretation of data sets from both GAIA and the Transiting Exoplanet Survey Satellite. It will also lead data-, compute- and theory-intensive collaborative research throughout the "Star and Planet" fields.

The most wide-reaching questions to be answered include:

1. How did the first and subsequent generations of stars produce and eject the chemical elements that enrich the universe?
2. How do stars and planetary systems form and evolve?

The key facilities and resources needed for Australian astronomers to answer these questions are:

A. Access to the largest adaptive-optics and high-resolution spectroscopic equipped telescopes in the world, equivalent to at least 20% of the Giant Magellan Telescope by the end of the decade.
B. Access to world-class supercomputer time at the level of one of the world's top-20 supercomputers to support observations with theoretical models of star and planet formation, stellar interiors and nucleosynthesis, stellar atmospheres and supernova explosions.
C. Access to 6-10 m class telescopes with a wide range of instrumentation, at the level of 100 nights per year (including adaptive optics prior to ELTs being fully AO equipped).
D. A center of excellence or equivalent focused on stars and planets, supported by a national astronomy fellowship scheme.
E. Access to a high spectral resolution, multi-object spectroscopy instrument equivalent to a 10% share in the Maunakea Spectroscopic Explorer.

[1] The metric in this case is survey speed compared to the Australia Telescope Compact Array at 3mm wavelengths.

1. Working Group Context and Structure

The Stars and Planets working group is very diverse, including very specialised observers and theorists, containing e.g. world experts in modelling of stellar atmospheres with millions of non-LTE lines and complex chemical reaction webs, non-ideal magnetohydrodynamics, fluid instabilities and dust formation where even a tractable framework is work-in-progress, big-data observers using multi-wavelength data sets, and instrumentation experts in interferometry pushing the finest scales of angular resolution. In recent history, our field has been a growth area, with 7 of the top 10 Australian astronomers in terms of 5-year h-index (excluding gravitational waves and neutrinos) researching Stars and Planets. New opportunities including those outlined below are expected to produce increased growth over the coming decade.

Prior to defining the biggest questions or resources, WG1.2 was split into 6 science subgroups, each of which considered the most important questions and discovery areas in the context of progress since the last decadal plan and what the next decade can bring. The two main executive summary questions were derived from Town Hall meetings, and are based on a series of related questions in the following sections from the Science Subgroups. Finally, a discussion of resources and opportunities, focusing on the biggest questions and those that are in common between multiple subgroups form the final section of this report, originally put together by the methodology-focused executive (Michael Ireland, Martin Asplund, Simon Ellingsen, Alex Heger, Amanda Karakas, Sarah Maddison and Chris Tinney). The detailed subgroup reports form the appendices, and include the names of subgroup chairs and other key contributors.

2. Science Subgroup Summary: Exoplanets

Key Questions

A. How do planetary systems form and evolve?
B. What is the structure and composition of exoplanets and their atmospheres?
C. Are habitable planets common, and do habitable planets contain life?

Discovery Areas

A. Finding planetary systems around bright or nearby stars that can be studied in detail.
B. Exoplanet spectra.

Opportunities

Exoplanetary research continues to expand rapidly. The rate of discoveries will continue to increase, especially with two new major discovery transit missions funded (TESS and PLATO). The field is moving past discovery to characterization (often requiring transits of nearby exoplanets) and population studies/multiple planetary system studies that will be crucial for answering questions of planetary formation and migration. The decade will see spectra of giant planets from ELTs and JWST, will see continued progress in the study of habitable worlds, and may see the planning and funding of transformative space missions (e.g. a visible light coronagraph e.g.WFIRST/AFTA, Exo-S,Exo-C).

Key Resources

A. Access to ultra-high precision radial velocity instrumentation on telescopes with apertures spanning the range 1-8 m, and eventually ELT by the end of the coming decade, for both exoplanet detection and follow-up.
B. Spectroscopic facilities for involvement in future space missions.

C. AO high-contrast imaging (including on stars to 15th magnitude) on the largest telescopes, in order to directly image giant exoplanets.
D. High performance computing access, for both dynamical simulations and atmosphere studies.

3. Science Subgroup Summary: Stellar Evolution and Nucleosynthesis

Key Questions

A. How did the first and subsequent generations of stars produce and eject the chemical elements that enrich the universe?
B. What happens in the late-stages in stellar evolution, right up to stellar death?
C. How do multi-dimensional hydrodynamic flows, magneto-hydrodynamics, binarity, and rotation affect the evolution of stars?

Discovery Areas

A. Stars as building blocks of Galaxies.
B. High-cadence transient searches, time-domain stellar astronomy observations and models.

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Opportunities

The next decade will be observationally driven by a number of ambitious space missions recently launched or soon-to-be launched (e.g., Gaia, Kepler, TESS, PLATO) by NASA and ESA, leading to a qualitative jump in our understanding of stars if we have the appropriate resources in place. These missions will typically observe across the whole sky, creating a strong link between stellar astrophysics and investigations of the Galaxy. We have the ability to lead large ground-based efforts to enhance the scientific output of such space missions, particularly aimed at the Southern sky. One example includes studies of asteroseismology using the results from Kepler, CoRoT, TESS and PLATO. Data from these missions will provide details of stellar interiors never before revealed including the extent of mixing (and overshoot) and internal rotation as a function of radius - all this as a function of mass, luminosity and composition (when combined with Gaia).

Binary interactions are now accepted as playing a vital role in the evolution and death of stars. This vastly increases the nature and variety of possible interactions able to be modeled by large-scale computer simulations, and will result in a reinterpretation of the evolution of stellar populations, stellar yields and galactic energetics.

Key Resources

A. HPC access on international competitive scale for multidimensional numerical modeling.
B. Cluster and cloud computing for stellar evolution and nucleosynthesis.
C. Support staff for code development, visualization, data analysis and data management.
D. Access to a next generation (8—10m class) high spectral resolution multi-object spectrograph in order to study the origin of the elements for the oldest stars in the Galaxy.
E. Long-duration, high-precision high-cadence time series data.

4. Science Subgroup Summary: Star and Planet Formation

Key Questions

A. What is the origin of the initial mass function of stars?
B. What are the other birth characteristics of stars, planets and planetary systems? (e.g. multiple star properties, masses and dynamics of disk products, chemical differentiation)
C. How do dust grains grow, migrate, evolve, disappear and form planetesimals in protoplanetary disks?

Discovery Areas

A. Theoretical simulations with realistic treatments of turbulence, magnetic fields, dust and radiation, on the scale of whole molecular clouds while still resolving formation of individual protostars.
B. High-spatial and spectral resolution observations of protoplanetary disks and star formation regions with ALMA.
C. High sensitivity observations with ALMA.

Opportunities

The next decade will see major advances in our understanding of the detailed processes through which both stars and planets form. ALMA will provide observational data with sufficient sensitivity and angular resolution to directly investigate the environment of young protostars on the scales where accretion occurs. We will determine if the highest mass stars form through core accretion or competitive accretion and study the growth and migration of grains in protoplanetary disks, forming the building blocks of planets. Accurate (few percent) distances to both low and high-mass star formation regions obtained through radio trigonometric parallax observations will complement Gaia parallaxes of non-extincted regions and will facilitate the development and testing of star formation simulations and the underpinning theories. Simulations will finally be able to resolve the full range of scales from molecular clouds all the way to individual protostars, with realistic treatments of the main physical processes in star formation, making ab-initio predictions for the initial mass function and stellar properties possible.

Key Resources

A. High-performance compute access in order to simulate the intricate physics in star and planet formation. As star formation is a difficult problem to scale, most useful are astronomy or institutional-specific supercomputers where individual simulations can run for months or years.
B. Access to ALMA data and expertise (plus ATCA at 7mm before ALMA band 1 and Mopra before survey observations with the ALMA compact array) to image the physics in protoplanetary disks.
C. Continued ability for VLBI parallax observations, to place extincted star forming regions in the larger context provided by ALMA, Gaia and infrared surveys.
D. Access to long-baseline optical/IR interferometry resources as they move down in sensitivity towards studying accretion onto protostars.
E. Increased flow of theoretical personnel into the Australian community

5. Science Subgroup Summary: Stellar Atmospheres and Spectroscopy

Key Questions

A. How do magnetic fields, convection and non-equilibrium processes affect stellar atmospheres, their spectra and the inferred stellar properties?
B. How are stellar oscillations, magnetic fields and winds generated in different parts of the

HR diagram and how do they interact with each other?
C. How are (exo)planetary atmospheres and their spectra influenced by external irradiation, global circulation and dust/cloud formation?

Discovery Areas

A. Disturbed stellar atmospheres: stellar atmospheres within an external potential, irradiated by an external source, polluted by an impactor (e.g., planet).
B. The interpretation of the radiation from exoplanets in terms of physical and chemical conditions in their atmospheres to eventually enable detection of bio-signatures.

Opportunities

Increased computational speed allows increasingly more physically realistic stellar atmosphere models, including self-consistent treatment of convective energy transport, magneto-hydrodynamical effects and radiative transfer in 3D, and time-dependent supercomputer simulations. The new generation of large-scale spectroscopic surveys of millions of stars necessitates new approaches for automated, robust and efficient analysis algorithms. A major challenge is how to incorporate physically more motivated modelling such as 3D stellar atmosphere models and 3D/non-LTE spectral line formation in these analyses to achieve the highest possible accuracy in terms of inferred stellar parameters and chemical compositions. The fields of stellar and planetary atmosphere modelling are becoming increasingly linked through similarities in physical processes (e.g. 3D time-dependent, magneto-hydrodynamics, global circulation modelling, non-equilibrium radiative transfer). The interpretation of exoplanet spectra is a major motivation to develop more physically motivated planetary atmosphere models.

Key Resources

A. High-performance computers to continuously increase the physical realism in the stellar/planetary atmosphere models and for predicting the resulting spectra for comparison with observations.
B. Access to high spectral resolution, multi-object spectrographs on telescopes of a range of apertures (1-4m, 8-10m and ELTs). A dedicated facility like the proposed 10m Maunakea Spectroscopic Explorer would be particularly valuable as Australia looks to maintain its world-leading standing in stellar atmosphere and spectroscopic modelling.
C. Access to data from the next generation of asteroseismology missions (TESS, PLATO) and solar telescopes (Solar Orbiter, EST, DKIST).

6. Science Subgroup Summary: Solar System

Key Questions

A. What can we learn from the solar system about the formation and evolution and properties of planetary systems in general?
B. Where are the habitable locations in the solar system and how do these evolve over time?
C. How has chemical composition evolved from that of the solar nebula to that of individual solar system objects?

Discovery Areas

A. New populations of solar system small bodies to be discovered in the next decade.

Opportunities

The next decade will see extensive exploration of the Solar system with space missions such as New Horizons to Pluto and the Kuiper belt, BepiColumbo to Mercury, and ExoMars carrying out the first exobiology experiments on Mars since Viking in 1976. Planned lunar missions include Chang'e 5 which will carry out the first lunar sample return since the 1970s. ALMA and JWST will provide new capabilities to study the composition of small solar system bodies.

Key Resources

A. High-performance computing facilities for orbital dynamics, planetary evolution and data analysis
B. Better mechanisms to allow Australian participation in international space missions.
C. High resolution IR spectroscopy on large telescopes for atmosphere studies.
D. JWST/ALMA access for studies of small Solar system bodies.

7. Science Subgroup Summary: Solar Physics

Key Questions

A. How is the solar magnetic field generated and how does it manifest itself? How does it contribute to coronal heating, and what are the fundamental processes in the explosive release of magnetic energy across many scales?
B. What determines the sunspot cycle, how can it be predicted, and how does it affect the Earth?
C. What is the Sun's detailed chemical composition? Is it possible to reconcile the spectroscopic evidence from the photosphere with the inferred composition of the interior using helioseismology?

Discovery Areas

A. The interaction between the solar interior, photosphere, and chromosphere through magnetic portals.
B. Forecasting using farside imaging and seismic detection of emerging magnetic flux.

Opportunities

Solar physics is currently undergoing major international investment. There are new 4-meter class telescopes currently under construction (DKIST in Hawaii) and in the planning stage (EST in the Canary Islands) with 25 km resolution. Current space based observatories SDO, Hinode; future Solar Orbiter will be providing many new data sets, with major new investment from Asia. More detailed stellar information (e.g. HERMES, asteroseismology post-Kepler) is providing the possibility for stronger links between solar and stellar research.

We also note that solar physics is very relevant in the context of the sun-earth connection (e.g. a Carrington-level flare would do more than $2.6 trillion damage to the global economy), and this aspect of solar physics is part of the space physics decadal planning process.

Key Resources

A. Critical mass of Australian solar researchers.

B. HPC access on international competitive scale for multidimensional numerical modelling.
C. MWA for studying solar fast radio bursts and planning for SKA.

8. Resources, Strategies and Opportunities

The capabilities needed to answer each of these questions are outlined in Table 1. *Precision calibration* is defined as better than 0.01 resolution element long-term astrometry/spectral shifts (e.g. precision radial velocity for exoplanet detection) or <1% uncertainty flux measurements, and *high dynamic range* is defined as $>10^3$ dynamic range imaging near spatial resolution limits. Wide field astrometry is not specifically listed because Gaia is expected to be transformative across science areas, and access to public data is expected to be sufficient for WG1.2. There are a range of facilities that can meet the capability needs. Such a detailed discussion is beyond the scope of the report, but we note that 1) Solar physics facilities (relating to the last 4 questions) tends to be very different to stellar/planetary facilities and 2) multiple scales of instrumentation are often needed, e.g. in high-performance computing, there is both a need for institutional or astronomy-specific computing and national computing infrastructure.

Table 1: The key science questions and the key capabilities that are required to answer them. Key: dark grey - very important, light grey - somewhat important, white – unimportant for the science question.

	Capability						Wavelength/Observable						
	Multi-Object	High Dynamic Range	Precision Calibration	High Spectral Resolution	<0.3 arcsec spatial resolution	Time-Domain	cm	mm/sub-mm	IR	Optical	Gravitational Waves	High Energy	High-Performance Computing
How did the first and subsequent generations of stars produce and eject the chemical elements that enrich the universe?													
How do stars and planetary systems form and evolve?													
What is the structure and composition of exoplanets and their atmospheres?													
Are habitable planets common, and do habitable planets contain life?													
What happens in the late-stages in stellar evolution, right up to stellar death?													
How does multi-dimensionality, (magneto-) hydrodynamics, binarity and rotation affect the evolution of stars?													
What is the origin of the initial mass function of stars?													
What are the other birth characteristics of stars, planets and planetary systems? (e.g. multiple star properties, masses and dynamics of disk products, chemical differentiation)													
How do dust grains grow, migrate, evolve, disappear and form planetesimals in protoplanetary disks?													
How do magnetic fields, convection and non-equilibrium processes affect stellar atmospheres, their spectra and the inferred stellar properties?													
How are stellar oscillations, magnetic fields and winds generated in different parts of the HR diagram and how do they interact with each other?													
How are (exo)planetary atmospheres influenced by irradiation, global circulation and dust/cloud formation?													
What can we learn from the Solar system about the formation and evolution and properties of planetary systems in general?													
Where are the habitable locations in the Solar system and how do these evolve over time?													
How has chemical composition evolved from that of the solar nebula to that of individual Solar system objects?													
How is the solar magnetic field generated and how does it manifest itself? How does it contribute to coronal heating, and what are the fundamental processes in the explosive release of magnetic energy across many scales?													
What determines the sunspot cycle, how can it be predicted, and how does it affect the Earth?													
What is the Sun's detailed chemical composition? Is it possible to reconcile the spectroscopic evidence from the photosphere with the inferred composition of the interior using helioseismology?													

Optical/IR :

- ESO provides the large telescope access required, both for 6—10 metre telescopes and ELT access. Assuming Australia would get 8% of competitive time (commensurate with the GDP fraction) this is equivalent to 26% of the GMT, 32% of an 8m and improved access to a HARPS-like ultra high precision RV instrument.
- High resolution spectroscopic capabilities on the world's largest telescopes is essential for leadership in the "first stars" and "chemical elements" kinds of science. Both secure 6-10 m access (e.g., for plan multi-semester projects) and ELT access is required.
- Planet formation and other high angular resolution science requires the largest telescopes. E-ELT is therefore strongly preferred, but GMT may be adequate if we have enough of a share (20%) to lead large projects and future instrumentation components.
- Access to infrared spectroscopy is also important for some science groups (e.g. for exoplanet characterization). This spectroscopy has to be at both low and high resolution. Studies of exoplanet host-star magnetic fields ("space weather" in exoplanetary systems) needs access to >2m or larger telescopes used for spectropolarimetry (e.g. ESO3.6m+HARPSpol). Taken together, the different meanings of "6-10m telescope access" in discussions with different subgroups could only be realized by well-instrumented 6-10m telescopes.

Radio/mm:

- ALMA is essential for the studies of Star and Planet formation and of evolved stars. Special Australian access is not required, but, e.g., a national workshop on using ALMA data (i.e., not funded by a single University) would greatly improve Australia's ability to use ALMA. Prior to construction of ALMA Band 1 Receivers the ATCA will provide critical information in the 7 mm wavelength range.
- Accurate distances are required to meaningfully compare observations with theoretical models. The LBA will provide distances to key low- and high-mass star formation regions (accurate to a few percent) through trigonometric parallax observations of interstellar masers and T-Tauri stars at centimetre wavelengths.
- Although there may be science links to SKA and the SKA prototypes, there is no core science in this working group other than LBA parallaxes needing wavelengths longer than 7 mm (there are some niche science cases, e.g., radio emission from young stars - although X-ray observations are equally useful).

Survey Science:

- HERMES and FunnelWeb will give Australia leadership in large spectroscopic surveys. Maintaining this leadership will require membership of an 8m class project, such as the Maunakea spectroscopic explorer. A membership level of 10% is needed in order to lead sub-surveys.

Other Observational Astronomy

- The coming decade may provide the first direct detection of gravitational waves from in-spiraling compact stellar remnants and supernovae explosions. Both the implications on rates in stellar evolution pathways and explosion physics is relevant to Australian researchers, who will be eagerly awaiting these results and planning observational follow-up.

National Facilities

- There will be a continuing need for access to national facilities with a broad range of instruments at optical and radio wavelengths. These facilities play a number of critical roles, including training of students, pilot projects to support/justify proposals to major international instruments and a range of science projects that require significant time allocations with modest sensitivity. The science undertaken with national facilities complements and supports that undertaken on international telescopes and provides a critical pathway for testing new ideas and techniques.

Theoretical Astrophysics:

- Flexible access to world-class high performance computing (HPC) resources are required for theoretical research in Australia to remain competitive. By flexible we mean access to both significant CPU hours across the science working groups (this requires a mix of facilities at both the national, astronomy-wide and institutional scale), and access to data storage and HPC support staff. By world-class, we mean access to one or more of the world's top 20 supercomputers based in Australia.
- Current 3D simulations of star and planet formation, stellar interiors, atmospheres, and supernovae require hundreds of millions of CPU hours across the Australian community. Following historic evolution of supercomputer capabilities, this will increase thousandfold by the end of the decade.
- These simulations currently produce petabytes of data that have to be analysed locally as they are too large to transfer. The storage requirement will increase according with the increase in CPU performance.
- To ensure access to computation resource for Australian researchers and to allow efficient analysis requires such computers to be located in Australia instead of relying exclusively on access to overseas resources or international collaborations; the latter should still be used to leverage supercomputer access.
- General purpose but astronomy-specific supercomputing would be preferable over specialised hardwares in order to allow portable codes running on different machines, and to allow a larger variety of codes to run and use the hardware.
- Professional support for code maintenance and development to adopt and optimize codes for current platforms.
- To supplement Australian HPC resources, access to overseas resources could be purchased, e.g., through AAL, in the same way this is currently being done for 8-10 m telescope time.

Appendices: Subgroup Reports

These reports expand on the summaries above, and provide context with progress against the previous decadal plan.

Appendix A: SCIENCE SUB-GROUP ON EXOPLANETS
Chairs: Rosemary Mardling and Daniel Bayliss

1. INTRODUCTION
Just 20 short years after the discovery of 51 Peg b, exoplanet research is at the forefront of modern astronomy, irresistibly attracting the next generation of astronomers and driving the instrumentation for future ground-based and space telescopes. With over 1800 planets now confirmed, a clear picture is starting to emerge which is exposing the rich diversity of planetary structure and system architecture, and in turn, Nature's preferred methods of planet construction.

Our view of the local galactic neighborhood has been changed forever; we now know that at least 50% of dwarf stars have planets and system architectures distinctly different to our own system, already partly answering the question: Is the Solar System typical or unusual? High precision and high resolution instruments in space and on the ground are starting to unveil the internal and atmospheric composition of planets, providing fundamental clues for answering one of mankind's oldest questions: "Are we alone in the Universe?".

One of the most striking features of the 21st-century science of extra-solar planets is its cross-disciplinary nature, bringing together researchers from astronomy, geophysics, atmospheric science, biology, physics and mathematics. And because of the youth of the discipline, mature scientists with diverse backgrounds are beginning to broaden their interests and contribute their expertise with relative ease. Moreover, the prospect of contributing to this exciting new field is attracting many of the brightest young minds from across the science spectrum.

2. KEY SCIENCE QUESTIONS

Here we describe the top three key questions for the next decade and two discovery areas:
a. The origins of planets. We now know planets are ubiquitous in the Galaxy, and thus planetary formation itself is a common event around newly forming stars. But is there more than one mechanism for planet formation and how does this depend on the star formation process? Why do some planets appear to have migrated from their birthplaces? The next ten years will see the origins of planets addressed both observationally and theoretically.

b. Exoplanet atmospheres. What is the structure and composition of exoplanet atmospheres? Could they support life? The first tentative steps have been taken towards probing the atmospheres of exoplanets, but results have been inconclusive and controversial. Specialized instrumentation will be needed to tackle this question, along with realistic models of exoplanet atmospheres.

c. Habitable Exoplanets. Though we know planets are common, we still do not if habitable exoplanets are common. And if habitable planets are found, do they contain biological lifeforms?

Primary discovery areas here are:
a. Finding exoplanets around bright or nearby stars that can be studied in detail.
b. Obtaining high quality spectra of exoplanets

PROGRESS REPORT

Many of the goals discussed in this section are now reality. There are over 1800 exoplanets known (cf 150 in 2005, an order of magnitude smaller), and the field has moved to focus more on the determination of planet properties and system architecture. Exoplanets have been directly imaged and the atmospheres of giant planets around bright stars have been studied using spectroscopy on 8m and space-based telescopes. Some projects did not go ahead (SIM, stable NIR echelle for Gemini, Exoplanet search on SkyMapper). Other projects did go ahead and have been very successful (CoRoT, Kepler, Transit Surveys, RV searches, microlensing discoveries).

Australia did achieve partnership in a 20m+ telescope, namely the GMT. Direct imaging of exoplanets will not be possible with first generation instruments GCLEF and GMACS. However GCLEF can characterise exoplanets and determine masses of exoplanets.

Australia did get access to 8m class telescopes. Magellan and Keck featured heavily in Australian exoplanet research over the last decade, primarily due to the hi-res echelles on those telescopes.

A multiobject high-resolution échelle was built (HERMES). However its usefulness for exoplanet research is unclear at this stage, as it has been optimised for galactic archeology science. Limitations for exoplanet research include limited wavelength coverage, stability of spectrograph, and limited spectral resolution (25,000 or 50,000). We still await an Australian purpose-built exoplanet instrument.

3) AUSTRALIAN EXPERTISE

A bullet-point list of key Australian expertise and strengths in the science area.
* Discovery of exoplanets - RV (UNSW, USQ), transits (ANU), Direct Imaging (ANU, USydney), Microlensing (UTas + Perth)
* Dynamics (Monash, USQ, Swinburne)
* Exoplanet Atmospheres (UNSW)
* Characterisation (ANU, UNSW, Monash).
* Stellar atmospheres (ANU) and asteroseismology (Usyd)
* Protoplanetary Discs (Swinburne, ANU)
* Debris Disks (UNSW, Swinburne)
* Formation theory (Swinburne, Monash)

4) KEY OPPORTUNITIES AND CHALLENGES

Kepler K2 (2014), ESPRESSO (2016), CHEOPS (2017) and TESS (2017) are the major new projects for RV and transit exoplanet discovery, with GPI (2014), Sphere (2014/15) and HiCIAO (current, ongoing development) being the major instruments for direct imaging at high contrast. The emerging field of "space weather", the interaction between stellar magnetic field and winds and exoplanets has potentially great influence on planetary habitability, and will take advantage of any new spectropolarimetric facilities that become available over the decade. Smaller RV, transit and microlensing surveys will continue, and will continue to expand (e.g. HAT-Pi). PLATO, EUCLID and WFIRST and any purpose built space-borne spectrograph look likely to fall outside the scope of this decadal review. Key characterisation work on ELTs and JWST however does fall within this decade.

Challenge - the future of exoplanet observations is space! This includes more integrated light missions in the short-term (e.g. TESS, PLATO) and coronagraphy and nulling missions in the future. How can Australia get involved? The most obvious way this decade (assuming no opportunities for direct Australian involvement in space missions) is ground based support for missions (target selection, follow-up). This means that we need 1,2 and 4m telescopes in Australia to continue to operate with significant time dedicated to follow-up characterisation of planet candidates from these space missions. Australia can capitalise on the tremendous opportunities for detailed characterisation by pursuing dedicated observational facilities for the critically necessary spectroscopic follow-up.

Appendix B: SCIENCE SUB-GROUP ON STELLAR EVOLUTION AND NUCLEOSYNTHESIS

Chairs: Alexander Heger, Dennis Stello

Members: Amanda Karakas, Orsola De Marco, Michael Ireland, John Lattanzio, Sarah Martell, David Yong, Simon Campbell, Michael Childress, Bernhard Mueller.

The big bang made only hydrogen, helium, and traces of Lithium; all heavier elements were synthesised in stars. This includes the material that makes up most of the rocky planets like Earth and the elements necessary for life. Yet many fundamental questions about the nature of the processes that make many of these elements and their isotopes remain unanswered. For example, we do not know the site and circumstances for the production of half of the heavy elements!

1) **Key Questions and Discovery Areas (an expansion on the questions in the main document):**

Questions

A. What is the origin of the elements from Carbon to Uranium? This question has several sub-parts, with the most uncertain elemental abundances arguably being the elements beyond iron.

B. What happens in the late-stages in stellar evolution? This question depends on stellar mass and environment (especially binarity) and there are unanswered questions from low masses (especially mass-loss mechanisms) to high masses (supernovae pathways).

C. How does multi-dimensionality and (magneto-) hydrodynamics affect the evolution of stars?

D. What is the influence of rotation, magnetic fields, and binary stars?

E. How do stars end their lives? E.g. which stars explode and how?

F. What are the progenitors of observed explosions

G. How do stars lose mass at each stage of their lives? How is this affected by initial conditions, and what causes the observed spread in mass-loss rates? How is the variety of possible end states for given initial conditions informed by mass-loss?

H. How do binary stars evolve and interact with each other? What observable effect do planets have on the evolution of their host stars?

I. How did the first stars in the Universe evolve, and how was this different from the evolution of subsequent generations?

Discovery Areas

A. Stars as building blocks of Galaxies.

B. High-cadence transient searches and time-domain stellar astronomy.

C. Integration with high-redshift (SKA, ALMA) and gravitational wave searches.

2) Progress against the last decadal plan in the science area

The last decade has seen tremendous progress in the investigation of stellar evolution. This has to a large extent been driven by space missions from Europe and the US and significant efforts from ground-based observations from both Australia and overseas. Contribution to all these efforts from Australian scientists has been significant. Examples include the discovery and analysis of four out of the five most iron-poor stars known to humanity.

Fundamental physics that governs stellar evolution (such as convection, rotation, angular momentum transport) can now be investigated with high fidelity through ultra-high precision photometric measurements from space and large scale ground-based spectroscopy of thousands of stars.

There has been significant progress in determining stellar abundances more accurately based on improved 3D and non-LTE stellar atmosphere models. We now have much more extended, and reliable, data sets on stellar abundances.

There was notable progress in identifying the progenitors of supernovae and gamma-ray bursts, leading to paradigm shifts on the late evolution and outcome of massive stars as well as what systems actually make Type Ia supernovae - or what they actually are - something that seems of key importance to their use as cosmological standard candles.

Pulsars provide a probe into the late evolutionary stages of massive stars. Australia has an outstanding record in the discovery of pulsars, with more than half of the 2300 known pulsars being discovered using the Parkes 64-m radio telescope. Many pulsars, especially millisecond pulsars, are members of binary or multiple systems and their properties provide a window into the evolution of these systems.

Nucleosynthesis models have become more refined, but the Big Question in the previous Decadal Plan still remains: "How do stars produce and eject the chemical elements that enrich the Universe?" For example, the r-process remains elusive, and the "Spite Plateau" for lithium remains a puzzle. Some new suggestions on the origin of the p-process have come up, and the "i-process" has gained attention.

Observational progress on stars and planets has been tremendous. The Kepler mission has allowed the entire field of planet hunting and asteroseismology to be revolutionised. The SkyMapper survey telescope is now operational, and has starting producing a large volume of data on ordinary stars and transient events around the Southern sky. 8-10m-class telescopes have become more widely available for studies of stellar spectra; however, Australia is now in danger of losing much of its access to these facilities.

There are now the first models that simulate stars in 3D although for some rather short or transient phases of stellar evolution or specific phenomena.

Note one field with Australian-led breakthroughs in SN Ia science. Wolfgang Kerzendorf and Brian Schmidt put out several papers (Kerzendorf et al. 2009, 2012, 2013, 2014 - part of Wolfgang's thesis at ANU) which presented a reconnaissance of the sites of Milky Way SN Ia remnants searching for surviving binary companions to the exploding white dwarf. The lack of surviving companions has been a leading line of evidence disfavoring a non-degenerate (i.e. MS or RG) companion, and the last decade has seen the SN Ia community collectively shift favour away from this progenitor scenario.

3) Key Australian expertise and strengths in the science area.

D. Stellar evolution modelling
E. Late evolution stages of stars
F. Supernovae and their progenitors
G. Nucleosynthesis in stars of all masses and in supernovae

H. Galactic Archaeology
I. Stellar and SN surveys
J. The first generations of stars in the universe
K. Asteroseismic observations and test of stellar physics
L. Simulations of stellar atmospheres
M. Simulations of binary interactions
N. Stellar clusters as test-benches for stellar formation and evolution
O. Observations (including instrumentation building) in both optical interferometry and spectroscopy.
P. Interpretation of stellar spectra and photometry (large scale surveys).
Q. Pulsar searching and timing.

4) Key opportunities and challenges in the science area.

Driven by a number of ambitious space missions recently launched or soon-to-be launched (e.g., Gaia, Kepler, TESS, PLATO) by NASA and ESA, there will be enormous opportunity for investigating stars in the coming decade and beyond. These missions will typically observe across the whole sky, creating a strong link between stellar astrophysics and investigations of the Galaxy. Experience shows that dedicated collaboration with space missions can significantly boost Australian astronomy. Such collaborations should be forged through our expertise in analysing and interpreting data from these missions, where possible and on contributing complementary observational data as well as theoretical models. Through this we can drive significant aspects of the science output generated by the next generation stellar astrophysics space missions. While Australia is not likely to compete directly with space programs from Europe and the US, we have the ability to lead large ground-based efforts to enhance the scientific output of such space missions, particularly aimed at the Southern sky.

Large-scale ground-based photometric and spectroscopic surveys (such as Skymapper and GALAH, respectively) need to be leveraged to create or maintain access to larger international telescopes, in collaboration with, e.g., ESO, US, and Japan.

The next decade will see a revolution in our understanding of stars, primarily because new observations from these large surveys will, for the first time, point out where the models are quantitatively wrong. We have never had access to such stellar data and the information within will lead to a qualitative jump in our understanding of stars - if we have the resources in place to extract as much information as possible from the upcoming data. Specific examples include studies of asteroseismology using the results from Kepler, CoRoT, and PLATO. These missions will provide details of stellar interiors never before revealed including the extent of mixing (and overshoot) and internal rotation as a function of radius. All this as a function of mass, luminosity and composition. This will provide strong constraints on theoretical models. ALMA will provide reliable mass loss rates out to the Magellanic Clouds, as well as rich information on isotopes (which could probably be obtained also with the ATCA and MOPRA). Reliable mass-loss rates are key to understanding AGB evolution and population synthesis. The very long time series of OGLE observations will reveal details of the binary interaction of red giants with orbiting planetary and stellar companions.

The important role binary interactions play in the evolution and death of stars has recently become unquestionable. Our current view of stellar evolution is almost entirely based on single stars. In the next decade we will quantify observationally the extent to which stellar phenomena are due to binary interactions or interactions between stars and their planets. We will determine the nature and variety of possible interactions, thanks to large-scale computer simulations. Pulsar studies will also provide observational constraints on binary evolution. Thus, we will reinterpret the evolution of stellar populations as well as redetermine stellar yields and galactic energetics. In turn this will feed on models of galactic formation and build-up.

With the next generation of scientists now also comes the opportunity for matching the observational progress by progress in computational studies. We need to simulate stellar phenomena like mixing processes and mass loss in order to study questions of the fundamental physics at work in stars, and we also want to be able to simulate increasingly larger phases of stellar evolution end-to-end; e.g., the late phases of massive stars, binary star interactions, or mixing during the helium flash and shell flash in low-mass stars.

Australian astronomy has invested \$12M into building the new HERMES instrument for the Anglo-Australian Telescope (AAT). This instrument makes use of the state-of-the-art existing infrastructure at the AAT, which represents a further \$20M investment and a 600-night 6-year large program on the AAT to conduct the Galactic Archaeology with HERMES (GALAH) survey has been submitted.

We cannot hope to reconstruct the entire Galactic history, even from measurements of the relative abundances of ~20 elements in a million stars (i.e., observations), unless we can understand where and how these elements were synthesised (i.e. theory). Despite a handful of papers essentially claiming "chemical tagging and Galactic archaeology does/will work", a major goal of the "Stellar Evolution and Nucleosynthesis" subgroup is to move well beyond this proof of principle and chart the evolution of our Galaxy over cosmic time. This will require a co-ordinated and considerable effort from both theorists and observers.

5) Most needed resources in the Australian context.

- People (including better ways to attract international students and postdocs)
- Supercomputing access for 3D MHD/hydro/radiation transport/stellar evolution and nucleosynthesis calculations
- Capability to perform world-class ground-based optical surveys and to do detailed follow-ups.
- Access to large telescopes including access to ELTs
- Access to interferometers that can resolve photospheres of stars at key evolutionary stages and study e.g. the physics of mass loss processes.
- An effort (CoE) similar to CAASTRO but geared at stellar astrophysics and astronomy, including optical astronomy

APPENDIX C: STAR AND PLANET FORMATION

Chair: Daniel Price

Members: Simon Ellingsen, Christoph Federrath, James Wurster, Mark Hutchison, Sarah Maddison, Mike Ireland, Sarah Martell, Jeremy Bailey, Phil Bland, Dennis Stello, Rosemary Mardling, Maxim Voronkov, Andrew Walsh

Star and planet formation in context

There are 100 billion stars in the Milky Way. And more than 100 billion galaxies in the Universe. But where did all these stars come from? What determines their properties? How long will they live for? Do they have planets around them, potentially harbouring life? We can answer these questions by studying star formation in the molecular clouds of the Galaxy. Ultimately we need to be able to model the physical processes by which these clouds convert gas into stars, in order to predict the properties of stars at birth. And to predict how the accumulation of dust and solid material leads to planets.

The highest mass stars are one of the key drivers in the evolution of galaxies over cosmic time. We can observe the rate of star formation through cosmic history how it correlates with merger rates and the activity of active galactic nuclei, but at present these are empirical relationships, as the details of the processes which govern the location and mass distribution of stellar formation remain unknown. Improved understanding of the details of how stars and planets form will have significant impact across many fields of astrophysics.

The Big Questions

1. How do stars, planetary systems, and planets form and evolve?
2. What are the birth characteristics of stars, planets, and planetary systems?
3. What is the origin of the initial mass function of stars?
4. Do high-mass stars form through core accretion or other processes (such as competitive accretion)?
5. What determines the star formation rate in the Milky Way, and in other galaxies?
6. Which planets (if any) form by gravitational instability, or by core accretion?
7. How do dust grains grow, migrate, evolve and disappear in protoplanetary discs?
8. Is terrestrial planet formation common, and what processes govern the bulk chemistry of Earth-mass planets?

NB: There is some crossover with the exoplanets subsection here, which is unavoidable due to close links between these groups.

Star and Planet formation research in Australia

Current Status

Australia's traditional strength in this area has been in areas related to radio astronomy, but has always had a small but highly regarded role in numerical simulations of star and planet formation. Areas of particular strength include:

1. Radio observations of masers in high mass star formation regions
2. Surveys of high mass star formation regions in the galaxy
3. The evolutionary sequence to massive star formation
4. Turbulence in the interstellar medium, both theory and observational
5. The role of magnetic fields in star formation, including non-ideal MHD
6. Numerical simulations of star cluster formation
7. Numerical simulations of dust and gas in protoplanetary discs
8. Computational methods for star and planet formation
9. Meteoritics (with crossover into Geology)
10. High angular resolution observations of young star systems

Researchers are spread across the following institutions:

R. Monash University (Price, Federrath, Wurster, Mardling)
S. Swinburne (Maddison, Hutchison)
T. UNSW (Bailey, Braiding, Burton, Cunningham, Jones, Rebelledo)
U. UTas (Ellingsen)
V. ANU (Ireland, Federrath)
W. CASS (Breen, Caswell, Dawson, Rathborne, Voronkov)
X. USyd (Stello)
Y. Curtin (Bland, Walsh)
Z. AAO (Martell)

Since the last review, relative to the goals of that review.
In the last decadal plan, star formation was split from planet formation. To quote from the WG1.2 report: "
we defer a discussion of star formation to the Decadal Review Working Group on The Nearby Universe.
".

- *Planet Formation (WG2.3 Report)*. Less progress has been made than hoped since the last decadal plan when compared to the ambitious goals of that report. Current simulations still do not have "sufficient numerical resolution and realism" to study processes of turbulence and magneto-hydrodynamics "properly". Incremental progress has occurred in many sub-fields, with many kinds of turbulence (e.g. two-fluid flows with dust+gas, multiple grain size populations) being studied, as well as much more detail in non-ideal MHD. Observations from ALMA have demonstrated the importance of 3D instabilities (e.g. van der Marel et al 2013), but have not simplified the model-inspired picture of planet formation. The promise of high-contrast cororagraphy has only just been realised, with the first truly high-contrast images coming out during this decadal planning process. In terms of general models of planet formation there has been significant progress from the solar system perspective. There has been a revolution in understanding of the dynamical evolution of the solar system - which maps nicely onto giant planet migration in exoplanetary systems. Sample-return from comets has given us a window into the composition of dust in the disk, and the degree of mixing in the disk. Improvements in geochronology and microanalysis have pinned early solar system processes to a timescale that provides a fine detail complement to astronomical studies of protoplanetary disks.
- *Star Formation (WG2.2 Report)*. This report essentially outlined massive star formation studies through masers as a discovery area. It is difficult to assess the progress against the last report as specific questions were not identified about the formation of individual stars (*but see the next sub-section where significant Australian contributions to massive star formation are outlined)*, however, there have been two major maser surveys relating to high-mass star formation over this period, both of which have and will continue to have significant international impact. The Methanol Multibeam (MMB) undertaken with Parkes and the HOPS survey undertaken with Mopra. The MMB has provided a complete census of young high-mass star formation regions throughout the Milky Way. The data from the MMB have demonstrated that there is current epoch star formation occurring in both the near and far side 3kpc expanding arms (something which was debated prior to Green et al. 2009, ApJ, 696, L156) and also to show which of the major molecular and atomic gas structures in the Galactic Centre region are accompanied by current epoch star formation (Green et al.

2011) The MMB and HOPS data are also being used for a range of star formation related studies, including their utilisation in an evolutionary timeline for high-mass star formation. The SPLASH survey, currently underway with Parkes is looking at both diffuse OH emission and OH masers and will provide by far the most sensitive and complete sample of maser emission from the ground state OH transitions. MALT-45 is a survey of class I methanol and silicon monoxide masers, relevant to both star formation and evolved stars. These will be other important resources for studying high-mass star formation in the Milky Way using masers. This report also highlighted the potential of JWST and ELTs to study planetary formation, both which proved to be beyond that decade. The report claimed that the 3mm upgrade would mean that ATCA would have real impact on low-mass star formation. There have been a few papers on this (e.g. Ubach et al, 2012, MNRAS) but impact was relatively low in an international context.

- The evolutionary sequence to massive star formation has been an area of significant Australian contributions over recent years. It was observations with Australian telescopes of methanol masers and the discovery of 'isolated' masers which led to the realisation that they pointed to a pre-UCHII phase of star formation (at the time thought to be the signpost of the onset of MSF). We now realise that the HMC phase, and a mm-only dense core phase precedes these, much of this the result of the efforts of Australian researchers (e.g. Hill T. et al, 2007, MNRAS 363, 405-451, ~80 citations; Longmore et al, MNRAS 379, 535-572, ~100 citations; Ellingsen, S.P. 2006, ApJ 638, 241, ~100 citations, Caswell J. et al 2010, MNRAS 404, 1029, ~80 citations). We note that most of this research falls within WG1.3 “The Galaxy”, as it is about star forming regions rather than individuals stars.

Observatories and facilities used by the Australian community

- Atacama Large Millimetre Array (ALMA)
- Australia Telescope Compact Array (ATCA)
- Mopra
- Parkes

Opportunities for the next decade

- ALMA is already revolutionising star and planet formation studies. Australians can already become involved with international time, but the community is under-using this capability.
- We can play a significant role in developing new computational methods for star and planet formation simulations (adaptive mesh refinement, smoothed particle hydrodynamics, sink particles, non-ideal magnetohydrodynamics, stellar feedback and sub-grid models, dust+gas models)..
- Existing Australian facilities can also provide the longer wavelength information which will be required for interpretation and understanding of many objects studied by ALMA, provided that they receive ongoing operational support
- Imaging of class I (or collisionally pumped) methanol masers with ATCA at 7mm is able to reveal kinematics and morphology of high-mass star forming regions in an unprecedented level of detail. Such data are not only complementary to ALMA results but also sometimes quite competitive (see examples in http://arxiv.org/abs/1401.5179). The surveys like MMB provided a solid foundation for a range of follow-ups, which includes interferometric follow-ups in the class I methanol transitions.

- Distances to southern high-mass star forming regions through maser parallax (closely related to "The Galaxy", but accurate distances to high-mass star forming regions are often crucial for analysis of individual objects).

What are the main questions we can answer in the next 10 years?

- What is the mechanism through which high-mass stars form?
- What fraction of star formation is directly triggered by an earlier generation (as opposed to some larger scale trigger such as spiral density waves)?
- How do dust grains grow, migrate, evolve and disappear in protoplanetary discs?
- What is the origin of the initial mass function of stars?
- What determines the star formation rate in the Milky Way, and in other galaxies?

What resources do we need?

- Continued access to supercomputing facilities, including large-scale (national, merit access), University-scale (immediate access) and Astronomy-only (mix of merit and flexible access). Flexibility is key here.
- Continued availability of state of the art receiver and backend systems covering radio/millimetre wavelengths at both low resolution (for large area surveys which provide statistical and population information) and high resolution (for detailed imaging of specific objects of interest).
- Instruments to facilitate sensitive high-frequency wide-area surveys (multi-beam/backends on Parkes/Tid?)
- Continued access to state-of-the-art microscopy, microanalysis, and geochronology techniques.
- Enhanced access to ALMA, including support for ALMA data analysis and proposals (e.g. enabled by ESO membership).
- Images at 0.1 AU resolution for nearby star forming regions at ~140pc, with the //Planet Formation Imager// (beyond the decade)

The Interstellar Medium White Paper

This document, which presents 9 big picture science cases relating to interstellar medium and star formation research and the opportunities for pursuing it in the coming decade, can be found an astro-ph at http://arxiv.org/abs/1307.0712. One science case deals directly with massive star formation, the others all impinge on the topic of star formation. The White Paper also discusses the capability needed to pursue this research.

APPENDIX C: STELLAR ATMOSPHERES AND SPECTROSCOPY

Chair: Martin Asplund
Members: Michael Ireland, Remo Collet, Jeremy Bailey

Introduction

The chronicle of the cosmos is written in starlight. Not only does the radiation from stars contain vital information about the stars and their histories, it also reveals the prevailing conditions before their births. Stars born at different times and locations can thus tell the whole story of the Universe from the earliest epochs a few hundred million years after the Big Bang when the first stars formed to the present day, from far-away galaxies to our solar neighbourhood. Unfortunately it is not possible to extract the stellar properties directly from observations of their spectra. To decipher the information encoded in the starlight requires having realistic models for the stellar surface – the stellar atmosphere – and how the emergent spectrum is formed there.

Fundamentally, standard models of stellar atmospheres have not changed much over the past half-century. While they have certainly improved in terms of input physical data (e.g. opacities) and completeness, the underlying assumptions still remain the same: gas in hydrostatic and thermodynamic equilibrium that does not change with time in a 1-dimensional (1D) geometry. Magnetic fields are ignored. Furthermore, the important convective energy transport is described through the rudimentary mixing length theory, which approximates convection with buoyant bubbles. Solar granulation – the observational manifestation of the solar convection zone at the surface – directly testifies that this is a poor description of the physics of convection, which is very much 3D, dynamic and varying in time where magnetic fields play an important role. Indeed most stars have convection zones reaching the surface, directly affecting the emergent starlight in a similar manner as in the Sun.

Recently, it has become possible to perform realistic time-dependent, 3D, magneto-hydrodynamical simulations of stellar surface convection and atmospheres for a wide range of stellar parameters. These numerical simulations have led to a fundamentally different view of how convection operates in stars: in contrast to the traditional view of buoyant bubbles raising from below as in the mixing length theory, the convection zone is driven by radiative cooling of the ascending gas at the surface that generates finger-like downdrafts while the upflows are broad and fundamentally the result of mass conservation. There is no unique mixing length: gas is overturning throughout the convection zone. Magnetic fields are prominent, giving rise to a wealth of phenomena at the surface, from small-scale magnetic flux concentrations to large-scale sun-/star-spots, active regions, prominences and coronal mass ejections. Magnetic fields also likely play a key role in heating the chromospheres and coronae as well as driving and shaping stellar winds. How stellar magnetic fields are generated in the first place is however still poorly understood.

Models of stellar atmospheres have dual purposes: shedding light on key physical processes such as convection and magnetic field interactions as well as enabling the prediction of stellar spectra and oscillations used to infer the key properties of stars (e.g. surface temperature, mass, radius, chemical composition, age). As such stellar atmospheres are windows both to the interiors of stars as well as their past and future. The myriad of atomic processes influencing the radiation field and thus the emergent stellar spectra together with macroscopic processes like convection and magnetic fields make this latter goal highly challenging but of utmost importance. Non-equilibrium spectrum formation often lead to level populations far from the Boltzmann and Saha distributions, which reshapes the emergent spectrum and thus the inferred stellar properties from observations. The ability to correctly model stellar atmospheres and their spectra underpins much of contemporary astrophysics and indeed cosmology as much if not most of our knowledge of the Universe stems one way or another from starlight.

Key Science Questions

- How are magnetic fields generated in stellar atmospheres and how do they manifest themselves for different stellar parameters?
- How does convection influence stellar radiation and oscillations?
- What mechanisms drive stellar winds across the Hertzsprung-Russell diagram?
- How are solar/stellar chromospheres and coronae heated?
- How does stellar activity and convection influence asteroseismology and exoplanet searches (transits, radial velocity)?
- How does non-equilibrium processes affect the emergent stellar spectra and thus the derived elemental abundances?
- What accuracy is achievable in inferred stellar parameters and chemical compositions from spectroscopy and photometry?
- How are planetary atmospheres affected by external radiation, global circulation and dust/cloud formation?
- How are planetary spectra shaped by the physical and chemical conditions in the planetary atmospheres?
- Can we detect bio-signatures in the radiation from exoplanetary atmospheres?
-

Australian Expertise and Strengths

- 3D radiative-hydrodynamical modelling of stellar atmospheres
- Simulations of magneto-convection
- 3D and non-equilibrium radiative transfer
- Stellar parameter determinations from spectroscopy and photometry
- High-resolution stellar spectroscopy
- Solar/stellar abundance analysis
- Extremely metal-poor stars
- Automated and accurate analysis of large stellar spectroscopic surveys
- Predicting emergent spectra from (exo)planetary atmospheres
- Interferometric observations of stellar surfaces
- Polarimetric observations of stellar winds
- Asteroseismology
- High-spatial and spectral solar observations

Progress Since the Last Decadal Plan

A major effort over the past decade has been to extend 3D, time-dependent radiative-hydrodynamical supercomputer simulations of surface convection from the solar case to a variety of different stellar parameters: from F-type stars down to the brown dwarf regime, from dwarf stars to red giants and from solar-metallicity down to the lowest metallicities.

While qualitatively stellar granulation remains similar there are many important differences as a result of the varying atmospheric conditions and energy fluxes needed to be transported. The first grids of such 3D hydrodynamical stellar atmosphere models covering a large part of the Hertzsprung-Russell diagram have now become available, which can be used for a large variety of applications from stellar spectroscopy and stellar evolution to asteroseismology and searches for extrasolar planets as they replace standard 1D hydrostatic model atmospheres. A major advantage is that the many free parameters (mixing length parameters, microturbulence, macroturbulence) that have hampered the fields of stellar atmospheres and stellar spectroscopy are now finally obsolete through realistic and self-consistent treatment of stellar convection, placing any prediction from such modelling on a much firmer foundation.

On the observational front, there are now very large sets of observed spectra, soon to be complemented by Gaia parallaxes. Optical and infrared interferometry has moved towards resolving surface features (e.g. pole brightening) on main-sequence stars, and when combined with polarimetry, has directly resolved the dust properties in winds being driven close to (or within) the photosphere of AGB stars. Kepler asteroseismology has shown how stellar parameters can be calibrated almost independently of stellar spectra – a resource that has only just started to be used in atmospheric model calibration.

The first models of the effects of magnetic fields on stellar atmospheres have appeared, demonstrating the key role they play in shaping the surfaces of stars and the resulting stellar spectra, including their effect on derived stellar elemental abundances. Impressive sun- and starspot simulations have been performed even if for computational reasons the magnetic fields are neither self-consistently generated nor extended throughout the convection zone; much work on the impact of magnetic fields in stars clearly remain.

As stellar atmosphere modelling has successfully extended to successively cooler stars and into the brown dwarf regime over the past decade, the fields of stellar atmospheres and (exo-) planetary atmospheres have become increasingly similar with much fruitful synergies. Traditionally the two communities have been rather separate but now with both facing the challenges of hydrodynamics, global circulations, the importance of 3D radiative transfer, complex chemistry/cloud/dust formation and similar processes, there is much more cross-talk, resulting in improved realism in the modelling of both types of objects. Of particular importance has been the ability to observationally probe the physical conditions in the atmospheres of exoplanets through for example transmission spectroscopy. The interpretation of such observations have benefitted tremendously from having access to sophisticated codes to predict the detailed spectra of such planetary atmospheres based on a complete inventory of atomic and molecular line opacities.

Complementary advances have been made in accurately predicting stellar spectra, including the ability to calculate departures from local thermodynamic equilibrium for a number of astrophysically crucial elements such as lithium, oxygen and iron for different types of stars. Such non-LTE effects have often turned out to be severe, which has necessitated sometimes drastic re-interpretations of observations with implications for fields like stellar evolution and nucleosynthesis, Galactic archaeology, extrasolar planets and cosmology. Recently even 3D non-LTE calculations have become feasible. Indeed the recent dramatic revision of the solar chemical composition – a fundamental yardstick in astronomy with far-reaching consequences for much of astronomy – has largely resulted from a much improved ability to model spectrum formation.

Important progress has also been made in handling the analysis of very large spectroscopic surveys of thousands or even millions of stars at high spectroscopic resolution, which are now coming online, such as SEGUE, APOGEE, LAMOST, Gaia-ESO survey and GALAH. Such large datasets require automated, efficient and robust yet accurate analysis techniques that can handle vastly different quality spectra for a wide range of stellar types. Here the development of the HERMES spectrograph on AAT have been pivotal as it enables the unprecedented GALAH survey of a million stars in the Milky Way, the largest and most ambitious stellar survey ever undertaken, which will run for the first half of the next decade. The construction of a multi-object, high-resolution optical spectrograph for AAT was a recommendation of the last decadal plan.

Opportunities for the Next Decade

Some of the key areas ripe for significant progress over the next decade include:

- The generation and manifestation of magnetic fields in stellar and planetary atmospheres in all its forms, from the smallest scales to sun-/star-spots and active regions.
- Understand how stellar chromospheres and coronae are heated through 3D MHD simulations with detailed radiative transfer and self-consistent excitation of acoustic heating from photospheric convective motions.
- Observations of stellar winds using e.g. spectrally-resolved and polarimetric interferometry.
- Detailed and self-consistent modelling of stellar winds and outflows across the HR-diagram.
- Investigating how (exo-)planetary atmospheres are affected by external irradiation, global circulation and/or cloud/dust formation.
- The interpretation of the radiation from exoplanets in terms of physical and chemical conditions in their atmospheres, driven both by increased realism in the modelling and improved observations from e.g. JWST and ELTs.
- Systematic exploration of 3D and non-LTE effects on stellar spectra for all types of elements across the HR-diagram.
- Developing automated and accurate abundance analysis techniques for the new era of million-star spectroscopic surveys that incorporate advances in 3D and non-LTE spectrum modelling to enable optimal inferences of stellar properties.
- Predicting the amplitudes and frequencies of stellar oscillations from 3D surface convection simulations to explain the asteroseismic scaling relations and quantify any departures from them for different stellar parameters.

Most Required Resources

- Personnel with the necessary expertise in high-performance computing, magneto-hydrodynamics, radiative transfer, atomic/molecular/dust physics and stellar/planetary spectroscopy
- Access to high-performance computers, including at least one national facility in the top-20 in the world
- Access to high-resolution (resolving power=20,000-100,000+), multi-object spectrographs on telescopes with a range of apertures, from small (1-4m) to large (6-10m) and the next generation of extremely large (>20m) optical/infrared telescopes
- Involvement in the next generation of large spectroscopic stellar surveys (4MOST@VISTA, Maunakea Spectroscopic Explorer)

- Access to optical and infrared interferometers
- Access to the next generation of asteroseismology missions (TESS, PLATO)
- Access to the next generation of solar telescopes (Solar Orbiter, EST, DKIST)

APPENDIX D: SOLAR SYSTEM

Jeremy Bailey - UNSW (Chair)
Phil Bland - Curtin
Graziella Caprarelli - Uni SA
Jon Clarke - Mars Society Australia/Australian Centre for Astrobiology
James Gilmore - UNSW
Jonti Horner - USQ
Frank Mills - ANU
Marc Norman - ANU

Key Questions / Discovery Areas

1. What can we learn from the Solar system about the formation, evolution and properties of planetary systems in general?

a) While our Solar system may not be typical, it is the only example of a planetary system that we can observe close up and in detail. Some key issues are:
b) Are the giant planets in our solar system consistent with formation by the core accretion or disk instability mechanisms proposed for other planetary systems?
c) To what extent did the giant planets migrate to reach their final orbits, and how did this affect the rest of the Solar system?
d) Surviving primordial solids (meteorites and interplanetary dust) contain a record of early solar system processes. Can we use that record to help model terrestrial planet formation?
e) What new populations of Solar system small bodies will be discovered in the next decade? Can we test models by predicting what populations remain undiscovered?

2. Where are the habitable locations in the Solar system and how do these evolve over time?

The study of habitability in the Solar system provides information to help constrain the habitable zone in other planetary systems. Some key issues include:

a) Did Mars and Venus have habitable conditions early in their history. If so for how long and what changed to render them uninhabitable?
b) What are the processes that cause loss of atmospheric gases to space and what is their relative importance for different planets?
c) How has the Earth's climate co-evolved with life over geological time?
d) Will the Earth go through a runaway/moist greenhouse event, causing loss of its water, similar to that hypothesised for Venus. If so how far in the future? Could our own actions trigger or avoid such an event?
e) Do habitable conditions exist on the icy moons in the outer Solar system?

3. How has chemical composition evolved from that of the solar nebula to that of individual Solar system objects?

Key issues include:

a) What caused the different degrees of heavy element enrichment in the giant planet atmospheres?
b) The bulk composition of the rocky planets is largely a result of a volatile depletion process. What caused that depletion?

c) Where did the Earth's water originate?
d) Can we use the chemistry of Solar system objects to provide an independent determination of where and when they formed?

Australian Expertise and Strengths

1. Fireball Network - The Desert Fireball network is now being expanded into a network of 60 cameras covering ~1/3 of Australia. The Australian location should allow a good success rate in recovering meteorites from observed falls, allowing the properties of meteorites to be linked to their orbits and origin within the Solar system (Phil Bland, ARC Laureate Fellow at Curtin).

2. Sample Analysis - Australia has considerable expertise in the analysis of Solar system samples including lunar rocks, meteorites and asteroid samples returned by the Hayabusa spacecraft (Marc Norman, Trevor Ireland, Yuri Amelin, ANU; Andy Tomkins, Monash; Fred Jourdan, Nick Timms, Steve Reddy, Gretchen Benedix, Phil Bland, Curtin).

3. Planetary Atmosphere Spectroscopy - Infrared spectroscopy of Venus, Mars, Jupiter, Saturn, Titan, Uranus and Neptune has been obtained using a range of facilities including the Australian built IRIS2 and NIFS instruments on the AAT and Gemini telescopes. The spectra are analysed using radiative transfer modelling (VSTAR) to determine trace gas and isotopic composition (e.g D/H) and distribution (Jeremy Bailey, Lucyna Kedziora-Chudczer, Daniel Cotton, UNSW).

4. Martian Geology/Mars Analogue Sites - (Jon Clarke, MSA/ACA; Graziella Caprarelli, UniSA; Penelope King, ANU;Malcolm Walter, UNSW; Gretchen Benedix, Marion Grange, Alexander Nemchin, Curtin).

5. Orbital Dynamics of Small Solar System Bodies - Analysis of the orbits and orbital evolution of small solar system bodies allows their populations to be studied and origins determined (Jonti Horner, USQ).

6. Atmospheric Chemistry - (Frank Mills, ANU)

Most Needed Resources in the Australian Context

1. High Performance Computing Facilities for Orbital Dynamics, Planetary Evolution and Data Analysis - Flexible next generation HPC resources, optimised for both large numbers of single processor jobs and parallel jobs.

2. Better Mechanisms to Allow Australian Participation in International Space Missions

3. High Resolution IR Spectroscopy Capability on Large Telescopes - NIFS (R ~ 5000) and GNIRS (R ~ 18000) on Gemini have been useful. Higher resolutions would be valuable (e.g. upgraded, cross dispersed CRIRES on VLT).

4. JWST for mid-IR spectroscopy - e.g for composition of small solar system bodies.

5. ALMA for mm/sub-mm spectroscopy - Composition and isotope ratios in comets.

APPENDIX E: SOLAR PHYSICS
Chair: Paul Cally

The Sun has been at the centre of astronomy since the beginning, and continues to play an important role.

The Role of Solar Physics
Astronomers study the Sun for several reasons:
1. It has been and continues to be one of our best laboratories for exploring astrophysical processes;
2. The wealth of available data on the Sun, its activity, and its oscillations far exceeds anything we have for other stars;
3. The solar chemical composition is a fundamental yardstick in astronomy;
4. The Sun is the primary template and comparator for solar-type stars, and in particular those that are being discovered to host planetary systems;
5. The Sun is a crucial driver of Earth climate, with significant implications for climate change over decades and centuries;
6. Its violent activity, in the form of coronal mass ejections (CMEs) and flares, determines space weather, with important consequences for the day-to-day health of spacecraft, telecommunications, power grids, and other technological systems.

Fundamental questions remain unanswered or controversial:
1. How is the solar magnetic field generated and how does it manifest itself?
2. What determines the sunspot cycle, how can it be predicted, and how does it affect the Earth? The current peculiar Solar Cycle 24 has thrown the cat amongst the pigeons, severely challenging all extant theories.
3. How can we predict or detect emerging magnetic flux days in advance? (Emerging flux may provoke flares and CMEs.)
4. What mechanisms heat the solar corona to several million degrees Kelvin? What are the relative roles of magnetic reconnection and waves in heating the solar atmosphere?
5. What are the fundamental processes in the explosive release of magnetic energy across many scales, from small scale reconnection events recently observed by Hinode to large X-class flares? How do these accelerate fast particles and cause other high-energy emission, including non-thermal radio emission?
6. Can we predict if, when, and how violently an active region will produce flares and coronal mass ejections (CMEs)?
7. What are the sources of the mass, momentum, and energy of the solar wind? How can its solar origins inform its structure and behaviour at 1 AU?
8. What is the Sun's detailed chemical composition? Is it possible to reconcile the spectroscopic evidence from the photosphere with the inferred composition of the interior using helioseismology?

How are Solar Physics and Space Physics Related?
Solar and space physics are intimately related, and the boundary between them can be fuzzy. Nevertheless, for the purposes of this review, we take solar physics to consist of studies of physical processes at and inside the Sun, including the atmosphere (photosphere, chromosphere, transition region, corona) but excluding the solar wind and its interaction with the Earth. Much research in solar physics though is motivated by questions from space physics, especially related to flares and CMEs, solar wind acceleration and composition, and

the solar sunspot cycle. The current 2010-2019 Decadal Plan for Space Science (Building a National Presence in Space) states that: *"The Sun is the ultimate driver of Earth's biosphere, human society, and the whole Earth system, including the circulation properties of the atmosphere and ocean. The Sun's variability influences climate and leads to space weather effects. Accordingly, many remote sensing and Earth observation data (including GPS, geodetic, and Global Navigation Satellite System (GNSS) data) depend intrinsically on space. This is not just because of the observing location and space weather, but also because many terrestrial regions probed with these data are coupled to space via solar radiation, energetic particles, and varying magnetic and electric fields. Understanding these effects is thus vital to Australia's use of Earth observation data."*
This indicates that the focus of space physics is ultimately the Earth. Space physics does not extensively address issues relevant to the Sun *per se* or to wider astronomy and astrophysics. Such questions fall within the purview of this astronomy and astrophysics review.

Australian Solar Research
Current Status
Australia has a small but active and highly regarded solar research community, as well as considerable expertise in space weather and the heliosphere. Particular areas of strength include:

AA. Helioseismology;
BB. Magnetohydrodynamic (MHD) theory and simulations of instabilities and shear flows;
CC. Radiative and convective modelling of the solar surface convection and atmosphere;
DD. Solar atmospheric modelling of observational signatures;
EE. Determination of the solar photospheric chemical composition;
FF. Magnetic field extrapolation from photosphere to corona;
GG. Observation, modelling, and prediction of solar flares;
HH. Use of low frequency radio observations to probe Coronal Mass Ejections (CMEs);
II. Statistical methods for modelling solar activity;
JJ. Non-thermal plasma processes in the solar corona.

The bulk of the researchers are at

- ANU (Martin Asplund, Remo Collet)
- Macquarie University (Birendra Pandey)
- Monash University (Paul Cally, Alina Donea, Sergiy Shelyag, Hamed Moradi)
- University of Sydney (Mike Wheatland, Iver Cairns, Geoff Vasil, Don Melrose,Dave Galloway (ret.))

These groups maintain active links with institutes and observatories around the world, and have access to many important data sources on the ground and in space. Australia also has considerable strength in Space Science with links to the Sun.

Since the Last Review
Solar physics did not figure prominently in the last decadal plan. However, the associated report by Working Group 2.3 identified two areas in which Australia could play an important role: Helioseismology and Interior Structure; and Solar Magnetism and Activity. Indeed, much Australian research has focused on these fields, with considerable success. Particular advances include:

- Australian helioseismology research (Monash group) over the past decade has focused on the seismology of solar activity, one of the grand challenges of the field, and has made great strides in (i) identifying and probing sunquakes, and understanding their links to flares; and (ii) recognizing the central role of MHD mode conversion in surface magnetic structures, with implications for interpreting their seismology and understanding how they channel wave energy into the overlying atmosphere. Particular expertise has been developed in Time-Distance helioseismology; Helioseismic Holography; large scale MHD simulation; use of low frequency radio data for probing solar activity; use of large data sets from space to which we have access.
- The group at ANU continues to be world-leaders in the modelling of solar surface convection and photosphere through 3D radiative-magnetohydrodynamical simulations. They have demonstrated that the latest generation of such 3D solar models is extremely successful in reproducing all of the key observational diagnostics and as such are highly realistic, making them trustworthy for various applications in solar physics.
- Martin Asplund (ANU) continues to lead the quest to obtain the most accurate solar chemical composition, which is a fundamental yardstick in astronomy and therefore has huge ramifications for most areas of contemporary astronomy. By means of realistic time-dependent, 3D, radiative-hydrodynamical supercomputer simulations of the solar surface convection and atmosphere coupled with detailed non-equilibrium spectral line formation calculations, his group has demonstrated that the Sun does not contain the canonical 2% of metals but rather 1.4%. This new solar chemical composition resolves many peculiarities in astronomy and in general works better but has wreaked havoc for helioseismology since solar interior models computed with this new composition has erroneous sound speed profile in the interior, especially immediately below the convection zone. This major problem has resisted a satisfactory solution for a decade now in spite of it being a very active research field involving solar/stellar physicists, spectroscopists, helioseismologists, planetary astronomers, atomic physicists and nuclear physicists among others.
- Advances in understanding solar activity (Sydney group) include: Developing methods for modeling coronal magnetic fields as nonlinear force-free fields (e.g. Wheatland 2000; 2007; Gilchrist & Wheatland 2014); improving understanding of solar flare statistics with application to solar flare prediction (e.g. Wheatland 2000; 2005); developing new models for solar flares (e.g. Melrose & Wheatland 2014); dynamo theory (Galloway); radio bursts/space physics/MWA (Cairns).

Active collaborations

Australian solar scientists maintain active international collaborations with many high profile international observatories and institutes. We list some here:

- High Altitude Observatory (HAO), NCAR, Boulder, Colorado, USA
- Max Planck Institute for Solar System Research (MPS), Germany
- Instituto de Astrofísica de Canarias (IAC), Spain
- North West Research Associates (NWRA, CoRA Division), USA
- Tata Institute for Fundamental Research (TIFR), India
- Queens University Belfast (QUB), UK
- Lockheed Martin Solar and Astrophysics Laboratory, California, USA
- CNRS, Centre de Physique Théorique de l'Ecole Polytechnique, France
- Institut d'Astrophysique Spatiale, Orsay, France
- Jeremiah Horrocks Institute, University of Central Lancashire, UK

- LESIA, Observatoire de Paris, CNRS, Université Pierre et Marie Curie, Université Denis Diderot, Meudon, France
- RHEA System S.A., Wavre, Belgium
- Royal Observatory of Belgium
- University of Oslo, Norway
- Copenhagen University, Denmark

Observatories and Instruments utilized by the Australian Solar Community

Space

- Solar and Heliospheric Observatory (SoHO) [NASA/ESA]
- Solar Dynamics Observatory (SDO) [NASA]
- Reuven Rhamaty High Energy Solar Spectroscopic Imager (RHESSI) [NASA]
- Hinode [JAXA/NASA]
- Geostationary Operational Environmental Satellites (GOES) [NASA]
- STEREO A and B [NASA]
- Interface Region Imaging Spectrograph (IRIS) [NASA]

Ground

- Global Oscillations Network Group (GONG) [US National Solar Observatory] (one of the six telescopes in the network is at Learmonth, WA)
- Murchison Widefield Array (MWA) [SKA precursor in Western Australia; partners from Australia, India, New Zealand, and the United States]
- National Solar Observatory (NSO, USA)
- Swedish Solar Telescope (La Palma, Spain)

Opportunities for the Next Decade

Currently, Asian solar physics is booming: Japan is going from strength to strength, including launching cutting-edge solar observatories into space (e.g., currently Hinode, with Solar C due later this decade), and both China and India are investing heavily in both personnel and planning large new ground-based telescopes (Chinese Giant Solar Telescope and National Large Solar Telescope respectively). South Korea and Taiwan are also active and growing. The epicentre of solar research is clearly moving toward the Asia-Pacific, presenting opportunities for Australia.

Due to active PhD programs, there is now a significant and growing diaspora of Australian solar researchers located in prestigious institutions around the world, many of whom would jump at the opportunity to return home if opportunities arose. This means that any decision to expand Australian solar research could be instituted at fairly short notice, and world-strength groups constructed.

The next decade will see a revolution in our ability to probe the Sun. Amongst the most significant innovations will be:

- The Daniel K. Inouye Solar Telescope (DKIST, formerly Advanced Technology Solar Telescope (ATST)) is a 4.24 m instrument currently under construction in Maui, Hawaii, to be completed in 2019.
- European Solar Telescope (EST) is a 4 m class instrument to be completed in the Canary Islands by 2020.
- Solar Orbiter, launch 2017 [European Space Agency] will achieve a highly elliptical orbit with perihelion 0.28AU and ultimately inclined over 30º from the ecliptic, giving an unprecedented view of magnetic fields and flows near the poles believed to be crucial to the solar dynamo.

- Solar C, launch 2018 [Japan] is expected to follow on from the highly successful Hinode (Solar B) spacecraft, and will provide high-resolution spectroscopic observation of the sun seamlessly from the photosphere to the corona during the important transition from the unusual Solar Cycle 24 to Cycle 25.
- Large ground-based solar telescopes are being planned for China and India, indicating these countries' serious entry into the field of solar physics.

Australian solar physics can benefit from each of these major and expensive international programs at little cost by collaborating internationally through current links and links yet to be developed.

The major research directions that Australian solar physics can take and prosper in over the next ten years are:

- Helioseismology of solar activity, involving theory, simulation, and observation
- High precision high cadence simulation of the lower solar atmosphere, including detailed calculation of radiative signatures and comparison with observations from the new generation of solar instruments, IRIS, ATST, etc.
- The most accurate determination of the solar chemical composition and how it relates to the chemistry of various planetary bodies and thus on the origin of the solar system
- Understanding the sunspot cycle
- Predicting magnetic eruptions (flares and CMEs), and using low frequency radio observations to connect them to the solar wind
- Modelling fundamental processes in flares.

The way forward for Australian Solar Research

The prime requirement for Australian solar physics is people. No-one with an Australian PhD in solar physics has found permanent employment in the field in Australia for over 20 years. Many younger Australian solar scientists have either been forced from the field, or forced from their country.

The way forward for Australian solar physics is clear. It needs funding for:

- Several permanent positions, in part to replace retiring researchers (Prof Don Melrose (Sydney) has already passed retirement age, though is still active, Dave Galloway (Sydney) has also recently retired, Prof Paul Cally (Monash) will reach retirement age later this decade).
- Several postdoctoral positions — these are crucial to maintaining and expanding Australian capacity in simulation and use of cutting-edge new instrumentation coming on line around the world.
- Modest support to assist international collaborations, in particular those that give Australian researchers access to new instruments and the data that comes from them.
- Computing, including adequate access to large scale computing clusters and small scale local computers for development, analysis, and graphics.

We do not propose to inaugurate any substantial new optical instrumentation here, but welcome the opportunities in radio exploration of solar activity afforded by the new generation of cutting-edge radio instrumentation in Australia (in particular MWA).

Most crucially, we recommend that Australia commit to supporting solar research in this country, and encourage universities to invest in the discipline. They will only do so if they have reason to expect regular funding in the field. Australia's focus on galactic and extragalactic astronomy has made it difficult to find funding or recognition for solar research in the last 20 years, but solar physics internationally is a vibrant and growing discipline with which "the sunburnt country" must engage. We can punch well above our weight for very moderate financial investment.