Stars and Planets

A Report to the National Committee for Astronomy for the Australian Astronomy Decadal Plan 2006-2015
By Working Group 2.3

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1 Introduction

The Australian *National Committee of Astronomy* (NCA) has charged the Working Group for Stars and Planets with identifying the most important research topics and the required resources in this area for input to the *Australian Astronomy Decadal Review for 2006-2015*. NCA specifically asked that planet formation and the Sun should be covered by this Working Group, while star formation and pulsars were to be diskussed by the Working Group on The Nearby Universe. Initially the Working Group had intended to cover space science and the Sun-Earth connection but after consultations with members of the *National Committee of Space Science* (NCSS) this was dropped. The reason for this is that NCSS has recently initiated its own decadal review process, which is lagging behind NCA's by at least 8-12 months. It was therefore felt that including space science here might preempt the diskussions and recommendations of NCSS.

Australia has a long and proud tradition in stellar astrophysics. There is currently a large and active community working in this area, covering a wide range of topics and with a high international impact. Planetary and extra-solar planetary science is poised to be the most significant growth area in astronomy over the next decade. Although the number of Australian scientists currently working in this area is not very large, they are in an excellent position to become international leaders in this field by exploiting niche expertise and synergies with other sciences. The number of scientists in Australia today carrying out research in solar physics and solar system research is relatively modest by international standards but their impact on the world-arena is large in several key areas. In the discussions below describing the challenges for the future, particular emphasis has been placed on the topics in which Australian astronomers have special opportunities to contribute in the coming decade.

2 The Big Questions

The National Committee of Astronomy asked in the remit to the various Decadal Review Working Groups that they structure their reports along the Big Questions in astronomy for the coming decade. Many of the questions normally identified in similar circumstances, such as the recent US and Canadian Astronomy Decadal Reviews, the US National Academy of Science report *Connecting quarks with the cosmos* and the Gemini Aspen-process, are directly related to research topics covered by this Working Group, as well as several more indirectly (such as *What is the nature of dark energy?* which can be probed by supernovae, and *How did the cosmic dark age end?* which may well have been caused by the first stars formed after the Big Bang). After diskussion within the Working Group the following high-level Big Questions in the area of stars and planets have been identified:

- How do stars, planetary systems, and planets form and evolve?
- How do stars produce and eject the chemical elements that enrich the Universe?
- What are the characteristics of stars, planets, and planetary systems?
- How common are planetary systems?
- Which astronomical environments have/had the characteristics needed for development of life?
- How do stars and their planetary systems interact?

In the following sections, these questions are discussed in more detail for the various subfields covered by this Working Group and placed in a framework of the necessary resources to address these crucial questions in the coming decade.

3 The Solar System/Planetary Science

Planetary science has been the most rapidly growing field of astronomy and astrophysics in the last decade and drives many of the most powerful and ambitious telescopes planned for the future. Although solar system science has a long tradition in astronomy, dating back to the ancients, the last ten years have seen an explosion in our knowledge of planetary systems in general, due to the discovery in 1995 of the first planet orbiting a Sun-like star. The last ten years have ushered in a new era of discovery, in which over 150 planets outside our own solar system, "extrasolar planets," have been discovered, most of them unlike any of the planets orbiting the Sun. The next decade will be focussed on characterization in planetary science, in which the important properties of these planets will be measured, allowing more detailed comparison of extrasolar planets with solar system planets. This journey of understanding is an inherently cross-disciplinary field with astronomy and earth sciences at its core, drawing upon chemistry, atmospheric physics, physics, and, recently, biology, to begin to understand the birth and evolution of planetary systems and the conditions that provide a cradle of life here on Earth and perhaps elsewhere.

3.1 The Solar System

Solar system science is a high profile area of modern science and addresses fundamental questions, such as understanding the current state of the solar system, how it evolved, and where life may exist/have existed. Some past discoveries have wrought deep changes on the philosophical underpinnings of society, as well as been a driving force behind many technological developments that have filtered into everyday use. Although a relatively small community, Australian solar system scientists at ANU, AAO and Macquarie in particular are playing key roles on the international scene in specific areas.

Planetary science is a multidisciplinary field of research and requires integration of many components to realize its full potential. These include interplanetary spacecrafts, Earth-orbiting satellites, ground-based telescopes, laboratory studies, modelling, and data analysis (ordered approximately from most expensive to least in terms of the facilities required). On the international level, the USA, Europe, and Japan are the only significant players in planetary studies involving Earth-orbiting satellites and interplanetary spacecraft. However, Australian research groups are making significant contributions at the component level to these endeavours. The remaining components of planetary science are all areas in which Australian scientists compete on roughly equal level with their international counterparts.

The key drivers for solar system exploration are the following:

- What are the key characteristics of the planets, moons and minor bodies?
- What is the past and future evolution of the planetary bodies?
- How do terrestrial planet atmospheres evolve with and without life and at a range of distances to the Sun?
- What conditions are required for development of life? Where were or are they found?
- What implications do these findings have for the future evolution of life on Earth?

3.1.1 Space-based exploration

Significant advances have been made in all of the above areas, particularly the first, as a result of interplanetary spacecraft, which have now visited almost all the planets in our solar system. Internationally, research efforts have shifted toward survey-type exploration of minor bodies and developing more detailed characterizations of the present state and past evolution of major bodies.

The USA, Europe, and Japan plan to launch a series of interplanetary spacecrafts and Earth-orbiting spacecrafts over the coming decade and Australian science can contribute in a number of ways. Particular areas of current or potential expertise are the following:

- Spacecraft and satellite operations via the Deep Space Network
- Technological developments for components of satellites and spacecraft
- Active membership of mission science teams
- Ground-based observing campaigns supporting spacecraft observations
- Laboratory-informed studies providing fundamental physical/chemical parameters for interpretation of spacecraft measurements
- Laboratory analyses of extraterrestrial samples returned by spacecrafts
- Numerical and theoretical studies of atmospheric and geophysical processes
- Interpretation and analysis of data from Earth-orbiting observatories and interplanetary spacecrafts

The most significant requirements for enhancing Australian participation in international solar system exploration endeavour lie not in funding, but in procedural matters. Most importantly, formal participation in an international spacecraft or satellite project often requires a government-to-government memorandum-of-understanding which cannot be negotiated by a university researcher or the ARC. Expansion of an existing international protocol to provide an umbrella under which Australian scientists could seek approval for formal participation in international projects would resolve a number of existing problems, such as USA export control regulations on munitions which are deemed to apply to anything related to satellites or spacecraft. In addition, active membership on a spacecraft science team requires commitment of travel funding for a multi-year period during which there is no science return from the commitment of funds. Thus, it is difficult to secure such funding through the standard routes (ARC, Australian Academy of Science etc).

3.1.2 Ground-based exploration

Ground-based facilities also play an important role in progressing our understanding of the solar system. Detailed mapping of the fundamental atmospheric properties of Mars (e.g. pressure, temperature, wind) could provide data for comparison with atmospheric circulation models, while the distribution of trace gases such as methane, water and carbon monoxide in the Martian atmosphere is of particular importance in view of their possible biological significance and impact for the greenhouse effect. Observations of Venus can be used to study the composition of the lower atmosphere (a region very hard to study with in-situ probes due to the extreme temperatures and pressures). Ground-based observations of the middle and upper atmosphere of Venus using spectrometers with much higher resolving power than can be accommodated in spacecraft provide a means of detecting trace gases that are important for understanding the chemical and evolutionary state of Venus' atmosphere. The surfaces and atmospheric compositions of the satellites of the outer planets can be studied spectroscopically (optical and IR) using ground-based telescopes. Furthermore, ground-based observations can provide a way of testing remote sensing techniques for subsequent use by spacecrafts and provide additional support observations for space missions.

The main requirement for ground-based solar system observations are visible and near-IR spectrographs working at resolving powers of R~1000-200,000 and capable of providing full coverage of a planet's disk. High spectral resolutions provide the necessary sensitivity for detection of trace atmospheric components, and provide a facility not currently available from spacecraft. Ideally these instruments should be fed by an adaptive optics (AO) system

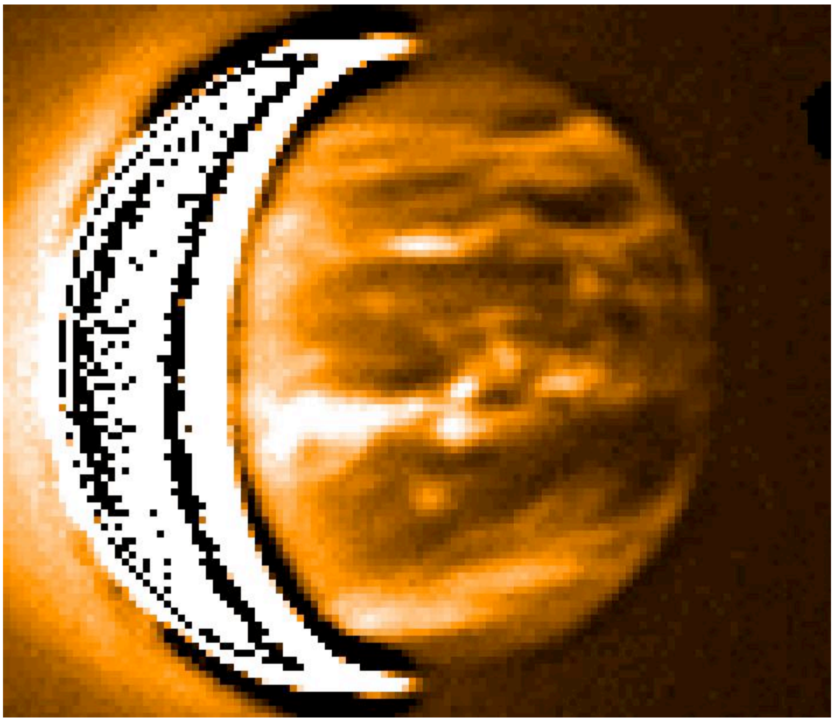


Image of Venus at 2.3 micron obtained with IRIS2 on the AAT (the daytime side of Venus on the left is saturated on this image). This shows the clouds silhouetted against the thermal radiation from the hot lower atmosphere. Images such as this can be used to study the atmospheric circulation patterns.

capable of working on bright planets such as Mars and Venus, which current AO facilities are unable to do. These systems should be located on telescopes with >4m aperture. ALMA and later SKA will contribute significantly to the imaging of Kuiper-belt objects and other minor bodies.

3.2 Meteoritic Isotopic Analysis

Primitive meteorites, known as chondrites, formed around 4,567 million years ago, when the solar system was a disk of gas and dust (the solar nebula) surrounding the early Sun. Such meteorites are mostly composed of small (~0.1 mm) chondrules but they also contain smaller amounts of other components such as calcium aluminium inclusions (CAIs) and Ameboid Olivine Aggregates (AOAs). These are amongst the earliest rocks that condensed from the solar nebula. Detailed isotopic abundance measurements of such primitive meteorites thus provide crucial information on the formation of planetary systems (as well as give insight to stellar nucleosynthesis through the pre-solar grains contained in the meteorites). Australia has for a long time played an internationally leading role in this research, particularly through work done at ANU and Monash. It is very important that the world-leading laboratory work made possible with the ANU-led development of ultra-precise ion mass spectrometers is give ample support in the future.

The formation of chondrules has for a long time remained a mystery with the recent discovery of extrasolar planets leading to a renewed interest in this problem. Chondrite components can now be dated accurately via U-Pb decay sequences as well as from short-lived radionuclides such as ^{26}Al. The preliminary results suggest that CAIs formed first,

Detailed isotopic abundance measurements of primitive meteorites and their constituents like chondrules, CAIs and presolar grains reveal the physical conditions during the earliest epochs of the solar system formation as well as the stellar nucleosynthesis in prior generations of stars.

then AOAs were produced around half a million years later, with most chondrules produced over a time of one to three million years after that. Thus, the most refractory material was formed first with generally less refractory material formed later. This is qualitatively consistent with the accretion behaviour of young stellar systems, whose mass accretion decreases over a timescale of around 3 million years. It also suggests that the solar nebula was homogeneous and well-mixed.

The origin of short-lived radionuclides in the solar nebula has been a subject of debate for long. For many years, discussion has centered around two basic models: formation by irradiation from within the solar nebula and/or formation via nucleosynthetic sources such as Asymptotic Giant Branch (AGB) stars and supernovae. Further theoretical analysis is required to clarify this issue. Can the short-lived radionuclides form from internal sources such as X-ray events from young stars or from cosmic rays interacting with the young stellar disk? How do supernova remnants interact with young stellar disks? Can radioactive dust that has nucleated/condensed from a supernova be injected into a young stellar system? These questions require a combination of nucleosynthetic and hydrodynamic codes.

More work on how planets agglomerated or condensed from the solar nebula is urgently needed. The primitive meteorites are the building blocks of planets and they in turn are simply agglomerations of chondrules, CAI and the like. Current dating techniques appear to indicate that lunar-size objects were present in the solar nebula by around 5 million years after the first rocks (CAIs) condensed from the nebula. It is clear that there was a significant thermal processing and transport mechanism that was operating over a three million year time span but the source of heating is as yet unknown. It is commonly thought that this heating occurred around 3 AU from the Sun and it may have been related to shocks from density waves, X-ray flares or planetesimal bow shocks. Imaging observations of other young stellar systems at even higher resolution would be helpful in determining which processes are at work. In addition, the majority of dust grains in comets do not consist of amorphous carbon as in the interstellar medium but of crystalline carbon, which forms in the inner disk regions (1-2 AU). This requires that chondritic material was thermally processed close to the Sun but was then transported to the outer disk. Similar conclusions are reached from the observations of dust in the inner disks of young stars. What is driving these outflows and how do they relate to the accerational infall onto the stars?

It is clear that further physical modelling is required to determine how the chondritic components were formed. There are many physical/isotopic/elemental attributes of these materials that remain unexplained such as the mass-independent ^{16}O enrichment observed in chondrites. Attempts to reproduce the conditions existing in the early solar nebula using specialised laboratory furnaces are required to study these processes.

3.3 Formation of Planetary Systems

“How do stars, planets and planetary systems form?” will be one of the critical Big Questions targeted by researchers in the coming decade. Here the diskussion is limited to studies of formation of planetary disks and planetary systems, while we defer a diskussion of star formation to the Decadal Review Working Group on The Nearby Universe. In Australia most of the theoretical/computational research in this area is done at Monash and Swinburne while the observational work is mainly being carried out at AAO, ANU, Sydney and UNSW.

The theory of planet formation is currently in a relatively primitive state. While the density and temperature profiles of protoplanetary disks are believed to be reasonably well understood, the dynamical processes leading to the formation of planets are largely unconstrained. During the early phases of gas cloud collapse, turbulence and magneto-hydrodynamics are obviously important but current simulations do not have sufficient numerical resolution and realism to study these processes properly. In addition, very large uncertainties plague existing models of grain growth and how small planetesimals subsequently develop into proto-planets. The existence of exosolar gas giant planets in very close orbits and/or eccentric orbits requires the presence of dynamical instabilities and planet migration during the early stages of planetary formation but no consensus has as yet emerged as to the mechanism(s) responsible. At large distances, is fragmentation or core accretion the dominant channel? The most popular theories for planet migration today involve either disk instabilities or disk-planet interactions but more theoretical and numerical work is clearly needed in this area. Such hydrodynamical modeling needs to include dust as well as magnetic fields, preferably using adaptive mesh refinement or smooth particle hydrodynamics techniques.

In view of the huge parameter space involved, there will also be a continued role for semi-analytical approaches. Planet-planet interactions, evolution of orbital elements from secular and dynamical instabilities and a better understanding of tidal effects are areas particularly amenable to such an approach. Observationally, a strong correlation between the probability of a star having planets and the metallicity of the star is now well established. Exactly how this comes about is not yet understood but it suggests that metal-rich cores need to form first in order for giant planets to develop. On the other hand, the dynamical effects of the star cluster environment at the time of formation may also strongly influence the presence or otherwise of planets around stars, and may partially explain the relatively low frequency of planets around stars surveyed so far. It may also be partly responsible for the existence of “free-floaters”, planets which have been liberated from their parent stars following the flyby of another cluster star, or following the disappearance of the protoplanetary disk which tends to stabilize the planetary system. Further outstanding issues still to be resolved are how planetary atmospheres and oceans are formed – are cometary/asteroidal impacts necessary to deliver the material for these? Finally, the exact mechanisms and ramifications in terms of tectonic and atmospheric evolution due to internal heating will require further investigations.

Observations of the dust emissions from planet-forming disks, both from thick still-forming disks and from thin “remnant” or “debris” disks, left over at the end of planet formation, are powerful probes of the frequency with which planets form. Characterization of dynamical structures in the scattered light from currently forming disks can reveal evidence for inner holes, gaps, and warps in the disks, which are indicative of the presence of forming planets. Older “debris” disks are more than just interesting leftovers. Because the patterns present in these disks are determined by internal interactions with the orbits of any gas giants present, observed structures have the power to indicate whether gas giants are present in the habitable regions of exoplanetary systems without directly detecting light from the planet itself. Crucial clues to planet formation also come from planet searches based on techniques (Doppler wobbles, transits, microlensing and direct imaging) that are sensitive to extrasolar planets at different distances, orbital radii, mass and size.

The most important observational facility for the coming decade to make headway in this field is extreme adaptive optics coronographs on 8m or larger telescopes. These should be capable of achieving 0.02 arcsecond spatial resolution and a $>10^7$ contrast ratio in 0.1 - 1.5 arcsecond radius. These should be coupled to near-IR (as the most interesting molecular signatures of this cold material is located there) spectrographs capable of a spectral resolving power of R~300. Nulling interferometry on 8-10m class telescopes, such as proposed with VLTI but also Keck and LBT, will provide imaging of the large-scale structure of proto-planetary disks. Interferometric millimeter observations facilitated by (for example) ALMA would be able to resolve the crucial spatial scales of proto-planetary disks and reveal their structure and composition. Infrared observatories like Spitzer and SOFIA will enable spectroscopic studies of these disks.

3.4 Extra-solar Planets

The detection of some 150 extra-solar planets in the past decade has galvanized the field of extra-solar planetary science. Exoplanetary science and astrobiology (the science that seeks to understand the building blocks of life and how they arose in the Universe) have become truly exciting and robust physical disciplines. For the first time in our history, astronomers are now in the position to ask, and answer, fundamental questions about the nature and numbers of planetary systems around other stars. For the first time, we can sensibly seek to ask, “How common are the life-generating processes that took place almost four billion years ago in our own solar system?”

A key point to emphasize here is that astronomers are not just targeting the discovery of one or two exoplanets – rather they are targeting the discovery of hundreds or even thousands of planets so we can determine planet frequencies, the distribution of orbital parameters, the measurement of atmospheric properties, etc. All these measurements are needed to develop a detailed understanding of how planetary systems form and evolve, in turn leading to an understanding of how common solar systems like our own are.

3.4.1 Direct detections

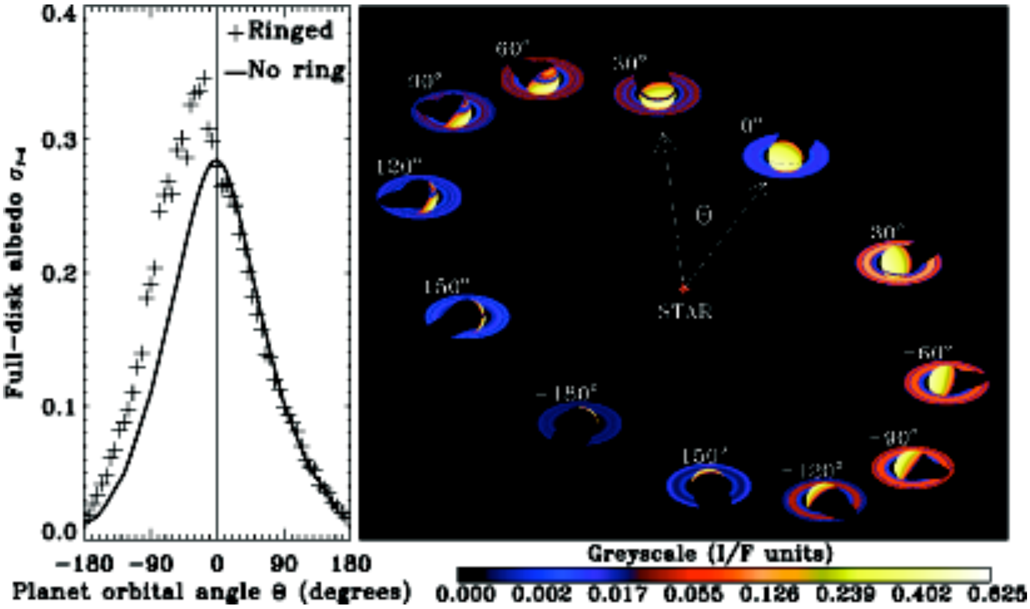
A key (indeed in many ways *the* key) scientific driver for the next generation of extremely large telescopes (ELTs) is the direct detection and characterization of planets like those in our own solar system: cold, (and thus relatively faint) gas giants like our own Jupiter and Saturn, and terrestrial exoplanets like Earth, with the eventual goal of the search for “biomarkers” on Earth analogs. Direct detections (by imaging) of large numbers of these planets are necessary to determine to what extent our own solar system is unique, and assess the probability that other planetary systems could support life. To perform these experiments will require:

- A large survey of about 1000 stars will give a large enough dataset to draw meaningful conclusions on the rarity of terrestrial planets. This requires reaching distances of about 30 parsecs from us. Because the projected separation between the star and its planets becomes very small (less than 0.1 arcsec) at these distances, an extremely large telescope (ELT) or a space-based interferometer like the Terrestrial Planet Finder (TPI) are needed to resolve them.
- Obtaining spectra of exo-planets to determine their surface properties (liquid or solid?) and search for "bio-markers" such as water, oxygen and carbon dioxide. The angular resolution and light-collecting power of an ELT is necessary to achieve this.
- Measuring planet orbits through multiple observations of each diskovered exo-planetary system. The orbital parameters (period and eccentricity) will determine the environment at the planet’s surface, and consequently its ability to support Earth-like

life.

- Studying entire exo-planetary systems by also detecting the larger giant gas planets in the outer regions of these systems (equivalents of Jupiter and Saturn). From this we can determine how common are systems with multiple planets of varying sizes (like are own solar system) and characterize the systems in different environments.

These observations are extremely challenging because of the extreme contrast between the bright central star and the faint planets near to it. For example, if the Sun-Earth system were observed at a distance of 30 parsecs, the Earth would appear at a projected separation of only 33 milli-arcseconds from its parent star, but the star would be 10 orders of magnitude brighter than the planet. Apart from the sheer collecting area of an ELT, which is especially vital for spectroscopic studies, the main advantage of larger telescope size is that the image of the central star can be made sharper (i.e. the diffraction limit is smaller), giving cleaner separation between the star and its faint companion planets. To achieve the goal of imaging terrestrial-size planets requires near-IR (where the planets are relatively bright) observations with an ELT having >30m aperture, which can deliver 0.005-0.002 arcsecond spatial resolution and $>10^{10}$ contrast ratio in 0.01-0.5 arcsecond radius. The presence of biomarkers can be deduced with low-resolution (R~300) near-IR spectroscopy. Placing such ELTs in Antarctica offers some attractive advantages for exo-planet observations. The telescopes capable of making these observations will likely come on line a few years beyond the timeframe of this decadal plan but design is underway now, and construction will begin in the next 3 to 10 years. Experience shows that Australia must engage with these projects early, both in terms of scientific direction and investment, if we are to play a key role in the eventual exploitation of these facilities.



An ELT capable of measuring contrasts of 1 part in 10^7 to 1 part in 10^{10} could determine whether Saturn-analogues orbiting distant stars have rings (crosses) or not (solid line) by detecting the complicated brightness and shadow variations rings cause in the reflected starlight as a function of time.

Dedicated exo-planet discovery space missions like Darwin and Terrestrial Planet Finder will provide another great means of directly image terrestrial-size planets around nearby stars using interferometry. While these will only be launched beyond the end of the decade considered here, there is a large amount of pre-cursor science required to optimize their design and observing campaigns, which Australia could play an important role in using facilities that will be available during the next decade.

A less challenging but very exciting problem is to directly detect light from gas giant planets orbiting other stars. To address the issue of just how common are systems with gas giant planets like our own requires the ability to detect a significant fraction (more than 10%) of the Jupiter-mass (or larger) planets orbiting older stars in Jupiter-to-Uranus-like orbits in nearby star systems. This will permit detailed study of the orbital properties of massive planets orbiting inside 5 AU, which will be critical to understanding the habitability of the inner regions of neighboring solar systems, and enable albedo measurements over a range of wavelengths, permitting a direct comparison of the atmospheres of these exoplanets with the solar system giant planets. Direct planet detection also enables the probing of entirely new classes of stars not accessible via indirect detection techniques. Finally, direct detection will enable the measurement of the precise mass of Doppler-detected planets and explore the detailed physical conditions of the atmospheres of each planet.

Direct imaging and spectroscopy of extra-solar giant planets should be achieved within the next 10 years using extreme adaptive optics facilities on 8-10m class telescopes. This requires facilities capable of 0.02 arcsecond spatial resolution, $>10^7$ contrast ratio in 0.1 - 1.5 arcsecond radius and spectral resolving power of up to R~300. Such observations are best done in the near-IR. Direct detections of gas giants should also be obtainable using nulling interferometry on 8-10m class telescopes. The requirements for imaging gas giant planets for both the extreme adaptive optics and interferometry approaches are technologically challenging and are pushing the limits of what can be accomplished with 8-10m class telescopes.

An ELT with 20-30m aperture would enable many more gas giants to be studied in detail than with extreme adaptive optics on 8-10m telescopes as well as explore a much wider observational phase space. Indeed should enable direct detection of at least some terrestrial-size extra-solar planets (the exact number is uncertain due to the unknown frequency of nearby stars with such planets).

3.4.2 Indirect detections

Complementary to the direct searches for exoplanets are indirect techniques like transit searches (i.e. searching for the dips in brightness seen when a dark planet partially eclipses the face of its parent star), radial velocity searches (i.e. measuring the tiny velocity perturbations induced in a star by the presence of orbiting gas giant planets), microlensing (i.e. searching for the light amplification of stars induced by gravitational lensing as a foreground object passes in front of the stellar disk) and astrometry (i.e. accurately measuring the variations in the position of stars caused by an unseen planet).

The overwhelming majority of currently known exoplanets have been detected by long-term, high-precision Doppler velocity programs operating on 1-4m class telescopes. These precision velocity programs rely on the spectroscopic observation of bright stars at signal-to-noise ratios of more than 200. These observations have to be repeated several times a year for many years (remembering that the orbital period of Jupiter is 12 years) for thousands of target stars. Because these observations are limited solely by photon-counting, they are equally suited to being carried out in large programs on 4m-class telescopes, as they are to small programs on larger 8m telescopes. As such it offers the current 1-4m telescopes in Australia a powerful scientific niche to continue performing front-rank astronomy throughout the next decade. These searches have both enormous intrinsic scientific value, and are critical to providing the target lists of candidate systems for direct detection of gas giant *and* possible terrestrial exoplanets in the years ahead with ELTs on the ground, as well as dedicated space-based planet finders.

The state-of-the-art Doppler programs today are being carried out by Australian, US and European astronomers using the AAT, ESO 3.6m, Keck I and other telescopes. In total around 1500 stars are being targeted by all these programs combined, and have led to some 150 detected exoplanets. However, the key to interpreting this database of planets is robust statistics and a detailed understanding of the formation mechanisms of exoplanets. To reach the systems with lower mass planets or gas giants like those in our solar system (negligible eccentricity, low mass and orbital periods >10 years) requires higher velocity precision, larger target samples and longer observational time baselines. The small radial velocity perturbations produced by terrestrial planets orbiting Sun-like stars are well below the meter-per-second velocity detection threshold of Doppler detection observing imposed by stellar properties (granulation, activity etc). However, astronomers can make headway in the search for low-mass planets, by targeting low-mass stars, where the reflex Doppler signature is larger. In cool M and L type stars, the velocity signatures of habitable planets are measurable with current technologies if the spectroscopic observations are carried out in the near-IR (more stellar flux, less spectral line crowding). This would enable astronomers to detect planets in the 1-10 Earth-mass range around hundreds of nearby, cool stars well before ELTs become operational. This requires high-resolution (R>70,000) near-IR spectrographs with wide wavelength coverage on 4-10m class telescopes. Such a spectrograph has been proposed as a second-generation instrument on Gemini.

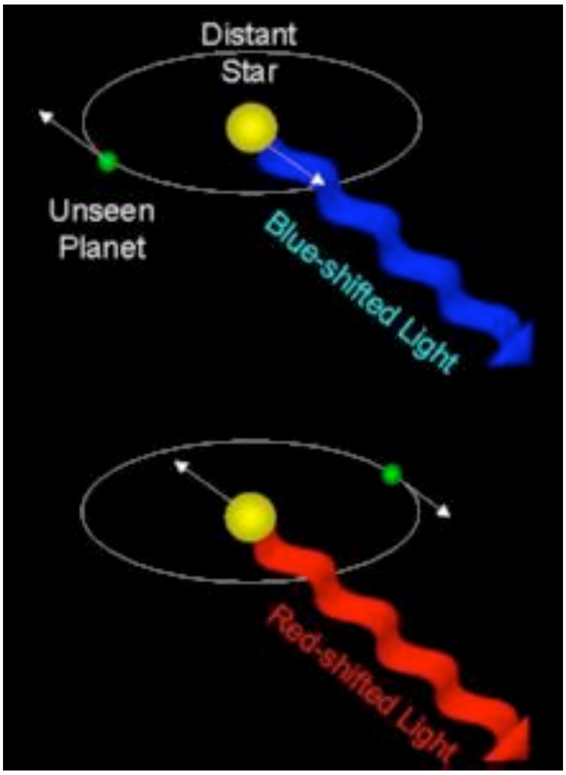


Illustration of how the radial velocity technique for finding extra-solar planets works. Because of the gravitational tug from an unseen planet, the spectrum of a star is periodically shifted towards the blue (when the planet is moving away from us and thus the star is approaching us slightly) and the red (when the planet is moving toward us). For giant gas planets in close orbits the radial velocity perturbation is 10 m/s or more while gas giants in an orbit like Jupiter would only move the stellar spectrum by 1-3 m/s. Very high spectral resolution and signal-to-noise observations are thus necessary over long periods of time to detect such companions.

Australia is in an ideal situation to make a quantum leap in planet searches within the next five years. The development of fibre robots at the AAO places Australia in an excellent situation to leverage from these existing technologies by developing a new multi-object spectrograph for the AAT. A new stabilized, large format, high-resolution echelle spectrograph fed by the existing fibre robot at the AAT would enable an immediate ~20-fold increase in planet searching efficiency, providing Australia with an exoplanet search capability more powerful than all other programmes in the world put together. Such an instrument would also be very powerful for studies of stellar pulsations (asteroseismology) and Galactic archaeology.

Extra-solar planets have also been discovered by the transit technique, which complements the radial velocity searches. A great advantage of this method is that it enables spectroscopic studies of the planetary atmosphere, which can be used to infer the physical conditions (temperature, pressure etc) and the chemical composition. The first spectroscopic studies have already been carried out in one exoplanet, resulting in the detection of sodium, oxygen and carbon in its atmosphere. Furthermore, since the transit signal is sensitive to planet size, whereas the Doppler signal is sensitive to mass, the two can be combined to yield a density measurement for exoplanets.

Since observable transits only occur under favourable viewing angles, very large-scale photometric stellar surveys are necessary to detect them. The brightness variation induced by the transit is very small unless the transiting planet is a giant, and hence photometric precision is vital. The necessary large sample sizes can be achieved either by observations of high-density environments like clusters or by using telescopes with very large fields-of-view. ANU's 1.3m Skymapper telescope (5-square degree field-of-view with ~1 arcsec resolution) currently under construction will be an ideal resource for transit searches and experiments are being planned now. Another exciting prospect is placing a wide-field 2m-class telescope on Antarctica to utilize the excellent seeing conditions, dark sky and long continuous observing runs offered at Dome C; smaller telescopes based in Antarctica such as Vulcan South are already performing such transit surveys. The European COROT (launch 2006) and NASA's Kepler (launch 2007) missions will perform space-based transit searches. Important follow-up work on transit-detected planets will rely on high-resolution spectrographs on 8m and larger telescopes in order to measure the corresponding Doppler signal, and to perform studies of planetary atmospheres in absorption against the bright parent star during the partial eclipse. Successful execution of large transit surveys require significant computing resources for data reduction, data storage and variability analysis, which are best addressed by supercomputing centers.

Another technique is microlensing, which to date has resulted in the detection of one extrasolar planet. The mass of a foreground star (and any planet that may be orbiting it) acts as a gravitational lens, modifying the amount of light detected from any background star that happens to chance across the line-of-sight. Microlensing can detect planets around very dim and/or distant planets as well detect very low-mass planets. However, enormous numbers of stars must be monitored in order to diskover the necessary chance alignment, and follow-up measurements are generally not possible since the photometric signature does not repeat. Australians have been among the pioneers in this technique in large international observing campaigns, first using it to constrain the amount of dark matter in the form of dark, compact objects in our own Milky Way, and later as an exoplanet search method and as a means to spatially resolve distant background stars. As with transit searches, microlensing requires very large numbers of stars to be monitored continuously across wide fields of view for long periods of time, and to very high (relative) photometric precision. In the next decade, survey science in microlensing is likely to make the biggest strides from sites of excellent seeing, but due to the need for continuous observations, the longitudinal coverage provided by Australia will be crucial. Very rapid, spectroscopic follow-up on 8m and larger telescopes is also needed to detect light directly from the lensing star, so that the mass and orbital distance measurements of any detected planet can be put on an absolute scale.

Exoplanets can also be detected by astrometric means using interferometry. The most notable among the various proposed missions is the Space Interferometry Mission (SIM). Although currently undergoing a rescoping due to budget costs, SIM is still expected to be launched by NASA in 2009. If micro-arcsecond astrometry can indeed be achieved, it would enable detections of terrestrial-size planets around the ~100 most nearby stars (<10 parsecs). With an accuracy of ~3 micro-arcsecond, planets the size of Neptune or larger could be detected around as many as 2000 nearby stars.

4 The Sun

4.1 Helioseismology and Interior Structure

The study of the frequencies and amplitudes of the solar oscillations gives a unique window into the interior structure of the Sun. This research field, known as helioseismology, has played a crucial role in astrophysics over the past few decades but has also had a major impact in other areas of physics, e.g. by convincingly demonstrating that the missing neutrinos from the Sun must have a particle physics explanation rather than being due to incorrect models of the solar interior.

Until very recently, solar evolutionary models taking into account element diffusion were spectacularly successful in reproducing the observed helioseismological data with typical differences in the inferred relative sound speeds on the 10^{-4} level. However, ANU-based astronomers have recently found that the solar photospheric abundances of C, N, O and Ne must be revised downward by almost a factor of two based on state-of-the-art 3D hydrodynamical modelling of the solar atmosphere. This wrecks havoc with the helioseismology comparison, causing approximately a five-fold increase in the sound speed differences. This problem has not yet been resolved but is currently a very active area of research involving astronomers and physicists alike. Regardless of what the final resolution will be (missing opacity, extra diffusion, unrealistic model atmospheres etc), it will have important consequences in other areas of astronomy.

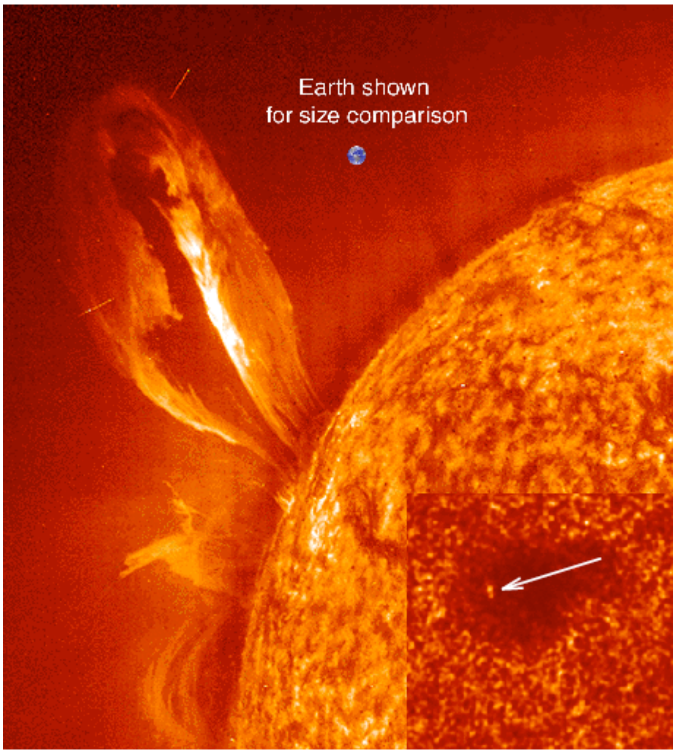
An exciting prospect provided by the solar oscillations is to map the 3D structure of large-scale flows, temperature inhomogeneities and magnetic field strength in the solar interior, using techniques such as local helioseismology and time-distance helioseismology. A major challenge for the future is to improve the spatial resolution these methods provide to reach the dominant physical scales of convection and magnetic fields. This will also require improved modelling to self-consistently include the effects of magnetic fields in these frequency inversions. Helioseismology can also map the interior rotation profile of the Sun, revealing a uniformally rotating radiative interior and the presence of a tachocline near the base of the convection zone. This introduces a shear layer that generates hydrodynamical instabilities and possibly magnetic dynamo action. A proper understanding of these phenomena requires improved numerical (magneto-)hydrodynamical modelling of convection and magnetic instabilities beyond that possible today.

Australia has a small but internationally prominent theoretical group based at Monash working in this area. The necessary observational data used in their analyses comes mainly from overseas solar observatories, both space-born (e.g. SOHO, RHESSI) and ground-based (e.g. the GONG network, which includes an observing station in Western Australia). The most important facility planned to come into operation on the 2006-2015 timescale is the NASA-led Solar Dynamics Observatory space mission. It is vital that the international solar physics community continues its admirable policy of providing open and immediate access to essentially all data collected. In that way, Australian solar physicists can continue to participate very successfully in this arena without a large financial investment in expensive solar facilities.

4.2 Solar Magnetism and Activity

Magnetic fields are obviously important in shaping the plasma in the Sun, in particular in the convection zone, photosphere, chromosphere and corona. The 11-year (or more correctly 22-year) solar cycle is one manifestation of this, but the solar observations reveal a swath of other phenomena like sun spots, flares and coronal mass ejections that are all driven by magnetic activity. Astronomers still do not agree on how these magnetic fields are generated in the first place. A combination of twist (convection) and turn (rotation) dynamo seems inevitable but whether a global or a local dynamo is at work is not yet clear. The solar magnetic fields may be produced by an alpha-omega dynamo operating near the base of the convection zone in the shear layer of the tachocline but other possibilities include flux transport dynamos induced by meridional circulation or local dynamos near the surface layers. To make progress in this area requires a better theoretical understanding of how convection, and in particular convective overshoot, and magnetic shear instabilities operate. One would hope that local helioseismology and magneto-hydrodynamical simulations can provide important clues in this respect in the coming years. Not until we have a full understanding of the solar dynamo, can we hope to be able to predict the levels of solar activity from cycle to cycle or the roughly bi-centennial timescales characteristic of the gap between grand minima like the Maunder minimum. Related to this are of course predictions of the total luminosity of the Sun (the solar constant) and how this may affect Earth's climate.

The solar activity also shows variations of timescales of days or shorter, which is driven by the magnetic fields generated in the interior and magnetic reconnection and the like in the outer layers. After all these years, astronomers still do not know how the solar chromosphere and corona are heated, although important progress has recently come from time-dependent magneto-hydrodynamical simulations. Another great challenge for the



A giant prominence on the Sun as captured by the SOHO satellite. As with other manifestations of solar activity, a prominence is a magneto-hydrodynamical phenomenon that ultimately are caused by the magnetic field generated by the solar dynamo in the interior. Events like promineces and flares can induce oscillations in the solar photosphere as shown in the insert. The solar flare of Oct. 29, 2003, produced a solar quake, which can be used to infer the temperature and magnetic structure of a sunspot below the surface.

future is to be able to predict solar activity, and therefore space weather. In particular this relies on the ability to detect and characterize emerging active regions on the far side of the sun, as well as to better predict the occurrence and size of solar flares, coronal mass ejections, and associated particle storms. This in turn will rely on improved near and far side helioseismological imaging techniques, modelling of complex magnetic structures, and statistical prediction schemes. One important issue that requires theoretical attention is how electrons and ions are accelerated in explosive events like flares and coronal mass ejections.

In Australia, work in this area is carried out at Monash (helioseismology, far-side imaging, active region analysis etc) and Sydney (dynamo theory, flare modelling etc). These groups have recently formed an Australian Solar Activity Partnership (ASAP) dedicated to observational and theoretical aspects of solar activity. The Australian community require continued access to data obtained from international solar observatories like SOHO, TRACE, GONG and the planned space-based Solar Dynamics Observatory to remain internationally competitive. This is a very data intensive research area, which necessitates a significant investment in manpower to handle the analysis and modelling.

5 Stellar Physics

5.1 Stellar Evolution and Nucleosynthesis

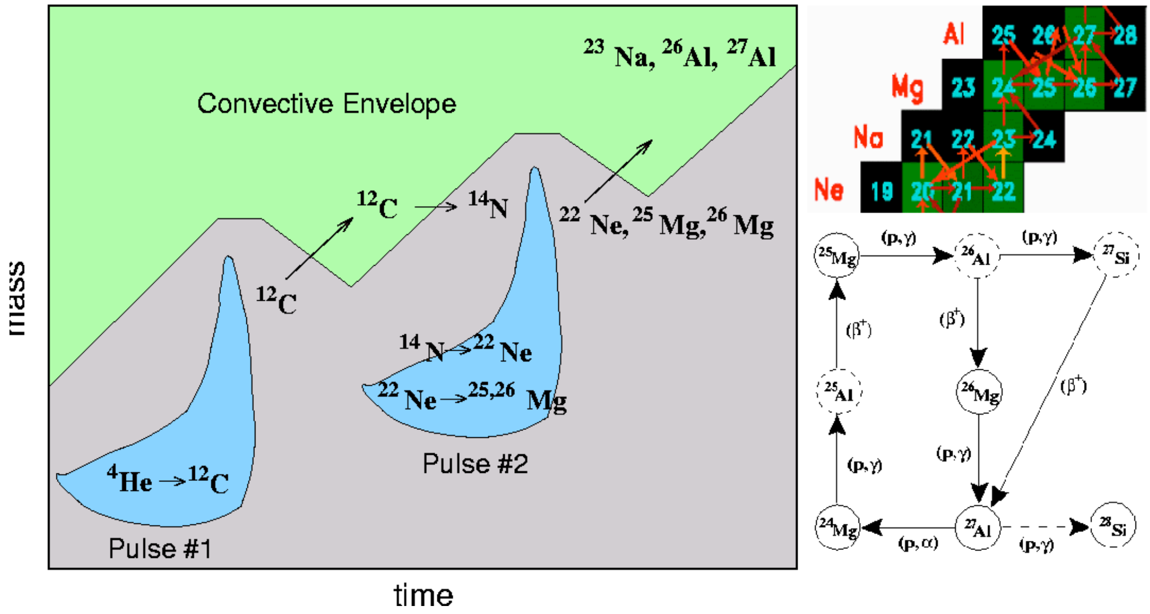
While stellar evolution is today quite a mature field of astronomy with a spectacularly successful track-record over the past century, many crucial ingredients are not yet well understood, which in turn impacts on many other areas of astronomy. No doubt the devil is in the details in this field. Indeed it is fair to say that perhaps the most challenging problems in stellar structure and evolution still remain. Since stellar evolution provides the underpinning for much of the astronomy of the future, such as cosmic chemical evolution, cosmic distance determinations and the evolutionary history of our own Milky Way Galaxy, it is vital to devote sufficient research into this area, both internationally and domestically. Today, Australia has only a relatively small amount of theoretical and numerical expertise in this field, located primarily at Monash; a strengthening in terms of additional manpower would be highly beneficial, in particular since the Australian community of observers relying on such computational predictions is quite healthy in terms of its size and productivity (ANU, Monash, Swinburne, AAO etc).

The focus of stellar evolution modelling in the coming decade will be to remove the many critical assumptions necessary today because of the enormous complexity of the problem. Dynamical processes like convection, pulsations and mass-loss (and their interplay which each other and with nucleosynthesis) play key roles in stellar evolution yet are still only included through parameterized and simple-minded approaches, a shortcoming which must be rectified. Likewise, the rapid late stages of stellar evolution such as supernovae, gamma-ray bursts and asymptotic giant branch stars are not self-consistently modelled today. Such time-dependent modelling will be very computationally demanding and thus require ready access to top-of-the-line supercomputers. Crucially, Australia does not have any local expertise in supernovae and massive star modelling nor in the emergent area of multi-dimensional hydrodynamic stellar evolution modelling, which appears to be a severe shortcoming.

The origin of the elements plays an integral part of modern astrophysics and as such feature prominently among the Big Questions for the decade ahead. All elements from carbon in the periodic table have been generated in stars. Theoretical stellar nucleosynthesis predictions are necessary ingredients in models of cosmic and galactic chemical evolution and thus have a myriad of applications and implications. Recent surveys (with very important involvement of astronomers at ANU in particular) have found stars with exceedingly low metallicities ([Fe/H]), revealing perhaps the result of *a single* nucleosynthesis event; new Australian-led surveys aimed at finding these very rare objects are planned. A striking feature of many of these extremely metal-poor and thus old stars is their very peculiar abundance pattern by solar standards, including enormous over-abundances of C, N, O and/or Mg, which may be the result of hypernovae in the very first generation of stars. These first stars (the elusive Population III stars) may also have provided the ionising radiation for the epoch of reionisation occurring a redshifts of $z>6$. Another example where stellar nucleosynthesis predictions provide the backbone of the interpretations are the anomalous elemental abundances observed in globular clusters, a thirty year old problem which has received a great deal of renewed attention recently because of the finding that these anomalies are present even in unevolved stars. Improved stellar evolution calculations for metal-poor stars can be expected to be a dominant theme for the coming decade.

High-precision isotopic abundance analysis can reveal the stellar productions sites of pre-solar grains from primitive meteorites, which requires a new level of detail from the stellar nucleosynthesis predictions. Such measurements of neutron capture elements can for example provide the neutron flux and hence conditions in the stellar interior. Australia is playing a leading role in these laboratory measurements, in particular through the groups at ANU and Monash. This work should continue to be encouraged and supported in the future.

The prospect of chemically tagging stars to probe galaxy formation and evolution also requires detailed predictions of elemental yields from different types of stars. The



Thermal pulses in AGB stars produce many elements and isotopes crucial for our understanding of the composition of the Galaxy. Here two consecutive thermal pulses produce primary ^{22}*Ne and the heavy isotopes of Mg are shown. These are then subject to proton captures via hot bottom burning and the Ne-Na and Mg-Al chains to produce primary* ^{23}*Na and both Al isotopes.*

Australian-based *RAdial Velocity Experiment* (RAVE) is measuring overall metallicities in hundreds of thousands of Galactic stars and similar Galactic projects will likely be carried out with AAOmega on AAT in the years 2006-2010. In about a decade the European Space Agency's will launch the *GAIA* satellite mission which will determine [Fe/H] and possibly [alpha/Fe] for *one billion* stars. Both of these employ a resolving power of R~10,000. In order to determine the abundances of more elements for large stellar samples require higher spectral resolution on multi-object spectrographs. Such capabilities on the 4m AAT and the 8m Gemini/Subaru telescopes would be extremely powerful facilities. In these Galactic Origins projects, stellar evolution modelling will play a very important role. Finally, the theory of stellar evolution also connects to observations at high redshift with for example the observed high abundances in the intergalactic medium, damped Ly-alpha systems and quasars still being largely unexplained.

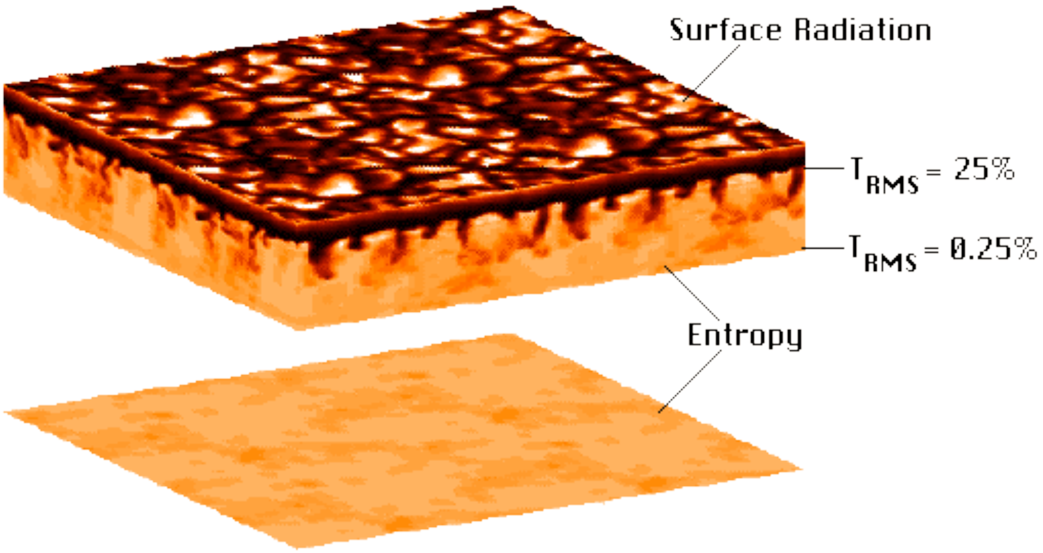
To make progress in this area, additional manpower is necessary, in particular with expertise in areas presently not existing in Australia today such as supernovae modelling and massive stars. Observationally the by far most important necessary facility in this area is high-resolution UV-optical-IR spectrographs on large telescopes. This enables measurements of the chemical enrichment at the stellar surface produced by stellar nucleosynthesis and can shed light on the poorly understood processes of mixing and convection that occur within the stars. Australia has no access to such a facility on 8-10m class telescopes, which has been to a tremendous detriment to the stellar community in recent years. It is clearly of utmost importance to rectify this pressing shortcoming in the immediate future. As stated above, such facilities should have multiplex capability and resolving power R>40,000 in order to be internationally competitive. It should be noted that similar instruments on other 8-10m class telescopes such as UVES on VLT, HIRES on Keck and HDS on Subaru are arguably some of the most successful instruments on these telescopes with great scientific returns. Explosive phenomena like supernovae and gamma-ray bursts are best studied through a combination of space-based telescopes (UV/optical/IR as well as gamma-ray/X-ray) and small to large ground-based telescopes with rapid turn-around time working in tandem. Very wide wavelength coverage is at a premium but relatively modest spectral resolving power sufficies.

5.2 Stellar Atmospheres

A proper understanding of stellar atmospheres and the spectrum formation processes is vital when using stars as probes of the Universe, since the atmosphere of a star is the region from which the bulk of the observed radiation originates. The theory of stellar atmospheres is therefore fundamental to much of contemporary astrophysics and cosmology. Important progress in this respect has recently been made both for hot stars and cool stars but much work still remains before stellar model atmospheres and spectral line formation can justifiably be called self-consistent with all the relevant physics included. Australia is well-placed to play a leading role in this endeavour.

In hot stars (spectral type O, B and A, but also supernovae, novae and the like), the intense radiation field determines both the properties of the atmospheric plasma and the overall stellar structure, e.g. by driving stellar mass-loss. The assumption of local thermodynamic equilibrium (LTE) is certain to break down, forcing a simultaneous solution of the radiative transfer equation, the rate equations for all atomic and molecular level populations and the hydrodynamical equations for conservation of mass, momentum and energy. It is now possible to construct time-independent, 1D, non-LTE, hydrodynamic model atmospheres with the effects of spectral line opacity (line-blanketing) incorporated. Observations reveal the presence of strong, time-varying shocks and inhomogeneities in stellar atmospheres. The great challenge for the future is therefore to go to time-dependent 3D hydrodynamical modelling while still retaining the current level of sophistication in the radiative transfer treatment. State-of-the-art modelling of hot stellar atmospheres already requires supercomputers, and the inclusion of these additional complexities will place even stronger demand on such facilities.

In cool stars (spectral type F, G and K), the greatest uncertainty in current stellar atmosphere modelling is the treatment of convection, since the convection zone reaches up to the stellar surface. While normally included through the rudimentary mixing length theory, convection is clearly a 3D and time-dependent phenomenon, which requires radiative-hydrodynamical modelling. Today, analyses of such stars rely on standard 1D hydrostatic LTE model atmospheres. Recently, 3D hydrodynamical model atmospheres of solar-type stars have become possible, to a large extent due to ANU-based astronomers. The great advantage with this type of modelling is that the standard fudge factors (mixing lengths, micro- and macroturbulence), which have hampered stellar spectroscopy for the past half-century, have now become obsolete. However, these models still have only an approximate treatment of the radiative transfer due to computing constraints, which must be rectified in the future through a full treatment of line-blanketing. As for hot stars, this will require access to massively parallel supercomputers. Since essentially all elemental abundance analyses of cool stars still today assume LTE, systematic studies of non-LTE spectral line formation for all elements and stellar parameters are necessary. This is critical when interpreting stellar spectra to study the origin of the elements and galactic and cosmic chemical evolution.



Three-dimensional hydrodynamical simulations of the atmospheres and outer layers of the convection zone in late-type stars show stellar granulation: warm, slowly ascending gas in the midst of cool, rapidly downflowing material which below the surface merge to form downdrafts. Such 3D stellar model atmospheres are now starting to be used to improve the accuracy of stellar abundance determinations.

For even cooler stars (spectral type M, L, T…), the main uncertainty is likely still the opacities, in particular from complex molecules. Dust and cloud formation are other important issues to address in the future. While Australia has world-leading observational astronomers working on brown dwarfs and similar stars, no theoretical/computational work is currently being performed within the country.

Having accurate stellar parameters like effective temperature, radii, luminosity and mass is paramount. Australia has a strong international reputation in stellar parameter determinations through research done at Sydney and ANU. Most of the methods employed today are model-dependent, and require realistic models of the stellar atmospheres and the spectral-line formation processes. Some model-independent techniques can achieve astonishing accuracy, but only for relatively few stars. These are therefore vital to calibrate other, more general approaches. The stellar interferometry group in Sydney operating the SUSI facility has a long history of being world-leaders in this area. SUSI has the highest angular resolution of any existing or proposed optical/IR interferometer. The only other southern interferometer, ESO's VLTI, will for the foreseeable future concentrate on wavelengths longer than 1 micron, whereas SUSI operates in the optical. This, together with its very high angular resolution, makes SUSI particularly well-suited to study hot stars (spectral type B and earlier). The combination of interferometry and spectroscopic observations allow the determination of masses and distances of spectroscopic binary stars. From the radial velocity variation and the variation in the angular diameter of Cepheid variables, their distances can be directly determined – a crucial step in the cosmic distance ladder. A proposed upgrade of SUSI involves linking the existing red- and blue-sensitive systems and upgrading the CCDs, which will give SUSI a unique narrow-band capability to efficiently observe stars such as Wolf-Rayet stars and OB stars.

The most important observational resource in the study of stellar atmospheres is no doubt having access to high-resolution (spectral resolving power up to 200,000) UV-optical-IR spectrographs to probe the atmospheric conditions such as temperature, velocity and chemical composition. In this context, the Sun is the ideal test-bed as its surface can be resolved in great detail with solar telescopes using adaptive optics (0.1" spatial resolution) and high-resolution spectrographs. Large telescopes will interferometric capabilities will be able to resolve the surfaces of nearby giants and supergiants and thus shed light on convection.

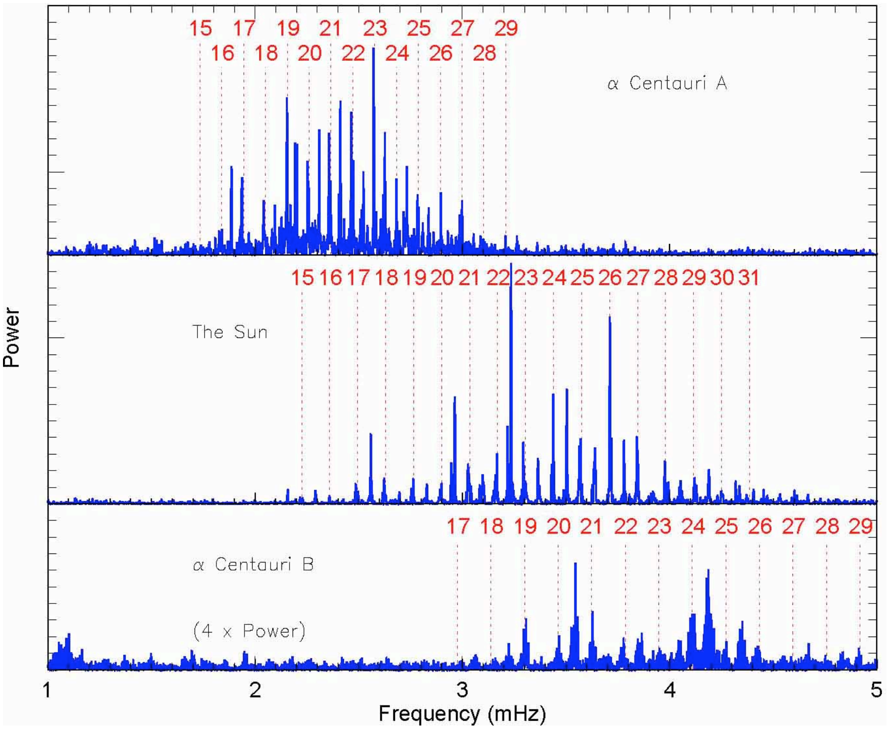
5.3 Stellar Variability

Stellar pulsations both provide a means to determine accurate distances to stars and to study stellar structure and evolution. Australia has a strong history of research into both observational and theoretical aspects of stellar pulsations, work done mainly at Sydney, AAO, ANU and UNSW. This research focuses on understanding these pulsations, particularly in red giant stars, and on using pulsation properties of stars to probe the internal structure (asteroseismology), most notably for stars like the Sun.

Red giants represent the final stages of stellar evolution. Given that many of the heavy elements are produced inside these stars and that the ejection of this enriched material into the interstellar medium is intimately linked to pulsations, it is clear that studying pulsations in red giants relates directly to the big question of the origin of the elements. The study of pulsating red giants has received a huge impetus from the availability of long-term photometric surveys such as MACHO and OGLE. Future work in this area will require efficient access to these and other large-scale photometric surveys. It will also require high-resolution spectroscopy to measure chemical enrichment at the stellar surface that is related to stellar hydrodynamic processes such as mixing and convection. These types of observations of red giants are key drivers for the IR high-resolution spectrograph recommended for the 8m Gemini telescopes by the Aspen process.

Asteroseismology involves using oscillation frequencies to measure sound speed, rotation and other physical properties of stellar interiors, providing powerful tests of evolutionary models. An exciting recent development has been the successful measurement of oscillations in solar-like stars like β Hydri and α Centauri A+B. UCLES at the AAT, as one of only a few spectrographs worldwide which is capable of achieving the required precision, has played a key role in this research, which has been carried out by astronomers at Sydney and AAO. These observations require coverage that is as continuous as possible voer several days and nights, and the longitude of Australia is a major asset. The key science questions for the coming decade include: How do the amplitudes and mode lifetimes of oscillations vary across the H-R diagram and how can this help us understand the complicated processes of convection that excite and damp the modes? In what areas are our understanding of stellar physics incomplete? How do convection (especially overshoot) and rotation affect the evolution of stars? How can we improve our models of old (metal-poor) stars?

Asteroseismological observations require extremely high-precision velocity measurements via high-resolution spectroscopy, coupled with long periods of continuous observations. Large apertures are needed for fainter targets such as the scientifically very important metal-poor stars and those in clusters, while 4-m class telescopes are ideal for more nearby stars. This implies continued availability of instruments such as UCLES, fed both by 4-m class



Oscillations in two nearby stars, alpha Centauri A & B, compared with those in the Sun. The graphs shows Fourier power spectra of high-precision velocity measurements. The observations of alpha Cen A & B were obtained simultaneously with the AAT in Australia and the ESO Very Large Telescope in Chile, and represent the most precise stellar velocities ever recorded. The regular series of peaks in each plot indicate the frequencies of oscillation in the three stars, and these give invaluable information about the sound speed in the stellar interiors.

telescopes, and also by larger ‘light buckets’. The efficiency would be greatly improved by having multiplex capability on such high-resolution spectrographs. It should also be noted that Antarctica has two obvious benefits for asteroseismology. One is the possibility for long uninterrupted observations from a single site. The second is the low scintillation, which should allow photometry with a precision second only to space telescopes. A 2-m class Antarctic telescope equipped with a CCD camera and/or high-resolution spectrograph would be a powerful instrument for asteroseismology.

The interpretation of the observed variability requires realistic stellar structure models as well as hydrodynamical modelling of the pulsations, preferably using adaptive mesh refinement to properly resolve the shocks that develop in Cepheids, RR Lyrae and similar stars. Today, such hydrodynamical expertise is largely lacking in Australia.

Late-type stars like the Sun generate magnetic fields through dynamo action. This magnetic surface activity introduces temporal variability in these stars. Solar observations reveal a plethora of such phenomena (sun spots, flux tubes, flares etc), most of which are only partly understood theoretically. These in turn link to the interaction between stars and their surroundings (winds, coronal mass ejections etc). Much theoretical work and magneto-hydrodynamic modelling is required in the future to understand these processes in detail. Many stars are expected to have much stronger magnetic fields than the Sun, most notably young, rapidly rotating and/or cool stars. These can be studied using Doppler imaging, which can map the stellar surfaces in terms of temperature, chemical composition etc. In Australia, this research is carried out mainly at USQ. Recently, magnetic Doppler imaging has become possible to reveal the 3D magnetic field structure, which requires spectro-polarimetric capability on high-resolution spectrographs. Such an instrument for the AAT with high efficiency would provide an interesting niche, since very few such instruments exist on similar or larger telescopes in the world today.

5.4 Stellar Systems

The majority of stars are members of stellar systems (binary, triple or higher). Many, if not all, stars are born in a stellar aggregate such as an open cluster or globular cluster, which may or may not disperse with time. The environment in which stars reside can have a profound impact on the properties and evolution of the stars. In close binaries, mass transfer can occur that affects the evolution of both companions. Such interactions modify the stellar chemical compositions, and consequently the stellar material that eventually enriches the interstellar medium. Mass transfer can give rise to a bewildering assortment of stars and phenomena, including supernovae (SN Ia), novae, cataclysmic variables, X-ray binaries, millisecond pulsars, symbiotic stars and many others. The end products depend on stellar evolution and the properties of the systems (masses, orbital parameters etc). To cover such a large parameter space requires fast stellar evolution calculations, a problem that is very well suited to parallel computing. Detailed hydrodynamical modelling on such stellar interactions continues to be a major challenge for the future, requiring massive supercomputing simulations when including all the relevant physics in 3D. It is embarrassing that the physics of SN Ia explosions is still not understood today in spite of their enormous importance for cosmology and origin of the elements. Another interesting phenomenon is mergers between compact objects: can neutron star mergers be responsible for gamma-ray bursts and what gravitational wave signatures would such events generate?

Stars located in crowded stellar environments such as globular clusters can experience particularly dramatic evolutionary effects. There, the perturbations on binary orbits are the most severe. Combining extensive nucleosynthesis with detailed binary evolution codes is something that is only now becoming feasible, as is the introduction of detailed nucleosynthesis in stellar cluster modelling. Today, however, the binary evolution is still parameterized rather than followed dynamically. Recent work done at Monash and Swinburne has for example studied how planetary systems can be affected by being located in open clusters, and how their diversity changes in clusters relative to the field. The next step in terms of modelling cluster evolution is to achieve direct globular cluster models with the N-body method. Open clusters are currently in range when using the teraflop GRAPE-6 special purpose hardware and petaflop GRAPE-8 machines should be available towards the end of the decade. Software development will also aid in increasing particle numbers especially when dealing with the evolution of binaries and other subsystems. Parallel implementation of N-body codes should also be explored. Ideally these N-body+stellar evolution calculations should be combined with hydrodynamical treatment of stellar collisions, using for example the smooth particle hydrodynamics scheme (which was originally invented in Australia).

5.5 Compact Stellar Remnants

White dwarfs, neutron stars and black holes, the three end points of stellar evolution, play important roles in modern astrophysics. Most of the theoretical work on compact objects is done at ANU and Sydney, while the majority of the observational studies is being performed at ANU, AAO and ATNF. From an observational point of view, this area requires access to 8-10 m class optical telescopes with spectropolarimetric capabilities and access to X-ray facilities.

Mergers between compact objects play an important role in many branches of astrophysics, but the details of the merging process are poorly understood. Further studies of type Ia supernovae (SNe Ia), which are associated with the thermonuclear detonations of white dwarfs in close interacting binaries and are used to infer the acceleration of the Universe, are urgently needed. Gamma-ray bursters (GRB) are likely related to collapsing massive stars that form black holes or to neutron star-neutron star mergers. Due to their enormous intrinsic brightness, GRBs can potentially be used to probe the expansion, reionization and chemical enrichment of the Universe during the earliest cosmic epochs and thus will attract a great deal of attention in the coming decade. An improved understanding of mergers between compact objects requires sophisticated 3D radiative-hydrodynamical calculations.

Detailed studies of field and cluster white dwarfs have led to a good understanding of the white dwarf mass distribution in our galaxy, and of the initial-final mass relationship for intermediate mass stars. A focus for the next decade is likely to be the extension of these studies to include neutron stars and black holes, and to investigate the initial-final mass relationship for high mass stars. For the neutron stars, this will become possible by directly studying their photospheres, and for black holes by studying their interaction with the inner regions of accretion disks. This requires an understanding of the evolutionary status of individual systems containing black holes, which in turn will translate through population synthesis studies to an understanding of the birth properties of black holes. This requires more attention to be given to binary star evolution, and to the stellar evolution of non-spherical stars.

Compact stars provide a unique opportunity to explore the behaviour of matter under extreme physical conditions (densities and magnetic fields) which are not achievable in terrestrial laboratories. The equation of state of neutron star interiors can probe the quark-gluon phase transitions, while their surface properties can verify quantum electro-dynamics and general relativity. The first measurements of neutron star temperatures are already becoming available from X-ray observations (e.g. Chandra and XMM), while it will soon be possible to study magnetic neutron-star atmospheres spectroscopically. As the magnetic field increases, the binding energy of the strongly bound state of hydrogen also increases so that even hydrogen may appear partially neutral even at temperatures of a million degrees. It should be possible to directly establish the masses and radii of neutron stars, and the surface magnetic field structure, through a combination of cyclotron and Zeeman spectroscopy, in similar detail to what has been possible with the magnetic white dwarfs over the past two decades. A better understanding of the atmospheric properties will translate through cooling curves to the probing of quantum chromo-dynamical properties of neutron star interiors and fundamental physics. During the past two decades magnetic white dwarfs have been used to verify atomic physics calculations of the Zeeman effect in hydrogen. Similar theoretical and observational studies of the Zeeman effect in other species such as carbon should be carried out.

The study of stellar-mass black holes is likely to be a major research area in the next decade. X-ray observations are already being used to establish the mass and spin of stellar-mass black holes in X-ray binaries. This requires an understanding the structure of accretion disks around Kerr black holes subject to appropriate inner boundary conditions, and the computation of the spectral properties of such disks allowing for irradiation and relativistic effects. More theoretical work in this area is needed. The observational database must include data from 8-10m optical telescopes to establish masses, and from X-ray telescopes to detect spectral features such as the iron fluorescence lines that carry vital information on the rotation of the black hole.

The origin of magnetic fields in compact stars is another major unsolved problem. The two possibilities are that the fields are of fossil origin dating back to the phase of star formation, or that the fields are generated through dynamo-action during subsequent phases of stellar evolution. To address this problem requires stellar evolution calculations that include magnetic fields and rotation in a self-consistent manner.

Hydrodynamical calculations of accretion disks in cataclysmic variables and low mass x-ray binaries and comparisons with observations have already provided constraints on the magnitude of the viscosity and the transport of angular momentum in accretion disks. Australian astronomers have played a key role in advancing this area through the modelling of stable and unstable disks using Smooth Particle Hydrodynamics (SPH). However, to remain competitive, these calculations need to be extended to allow for radiative transfer, and for different prescriptions of viscosity involving magnetic fields in the disk. The presence of a magnetic field anchored to the central object can also have a dramatic effect on the nature of the flow (e.g. formation of jets). The accretion disk - magnetosphere interaction is important in many branches of astrophysics and is a major unsolved problem in astrophysics.

6 Recommendations

To make headway on the exciting topics outlined in the previous sections requires substantial resources in terms of manpower and facilities. In the discussion below we have divided the recommendations of the Working Group into (1) facilities requiring significant Australian financial investments, (2) international facilities without direct Australian financial involvement but which Australian astronomers require access to and (3) human resources. In the first category, we have made a prioritisation for future facilities for the area of stars and planets.

6.1 Facilities requiring significant Australian financial investments

The Working Group strongly recommends Australian participation in the next generation of ground-based optical/IR extremely large telescopes (ELT) with apertures of 20m or larger. As outlined above, perhaps *the* key motivation for building such telescopes is the potential to directly image and spectroscopically characterise planets around other stars. Australia cannot afford to miss out on this exciting opportunity, which will shape and drive much of the international astronomical research in the coming decades.

In addition, ELTs will enable a much better understanding of star and planet formation as well as stellar evolution and nucleosynthesis by allowing detailed studies of distant and rare stars, such as the elusive first generation of stars born after the Big Bang.

We strongly recommend increased Australian involvement in 8-10m class optical telescopes equipped with multi-object high-resolution optical-IR spectrographs, extreme adaptive optics and interferometric capability. It is absolutely vital that Australian astronomers significantly increase their share of 8-10m class telescopes with a full suite of state-of-the-art instrumentation beyond the current ~6% share of the Gemini telescopes. The lack of Australian access to an efficient high-resolution optical spectrograph on an 8-10m class telescope must be rectified immediately. From an Australian perspective, the most important science areas these facilities will address are stellar evolution, origin of the elements, Galactic archaeology, planet formation and detection of exoplanets, which are key research themes in Australian astronomy today.

Involvement in an ELT project and increased share of properly equipped 8-10m class telescopes are the two top priorities according to this Working Group. In addition, we have identified three further very important items:

We recommend access to national supercomputing facilities that are internationally competitive, i.e. among the top-50 supercomputers in the world. As clear from presentation of the various scientific areas above, supercomputer simulations are crucial ingredients in modern stellar and planetary science. Only by incorporating all the relevant physics into the simulations and having sufficient numerical resolution, can the results and interpretations be trustworthy.

We recommend the construction of a multi-object, high-resolution optical spectrograph for AAT. This would be a very powerful tool for exo-planet searches, asteroseismology and Galactic archaeology, which are all areas in which Australia is currently playing internationally leading roles. Such an instrument in combination with devoting large amount of observing time for such projects would be an excellent niche for AAT on the world scene in the era of 8m and larger telescopes.

In addition, there are a large number of other new facilities requiring financial investment which this Working Group recommend that Australia participate in, albeit with a lower priority than the above-mentioned top priorities. A high-resolution spectropolarimeter for AAT would shed light on stellar activity and planet formation among other things. No such facility currently exists in the southern hemisphere and thus it would offer a unique niche for AAT to exploit. An AO imager coupled with an optical/IR spectrograph would be very useful for observations of solar system bodies and should be explored further for AAT. A further upgrade of SUSI by combining the red and blue capabilities with new CCDs would improve the accuracy of the derived stellar parameters. Even higher-precision ion mass spectrometers for meteoritic isotopic abundance measurements are important for retaining the lead Australia currently enjoys in this field. On the computational side, special-purpose machines like the GRAPE computers for N-body calculations would be used extensively in stellar system and planet dynamics studies. **The Working Group recommends that sufficient funds are set aside for such projects which can be applied for in a competitive allocation procedure.**

Although ALMA and SKA are two major international facilities that will have pivotal impact on many areas of astronomical research, the Working Group on Stars and Planets does not place participation in these projects at as high a priority as the above items.

6.2 International facilities without direct Australian financial involvement

In the coming decade, Australia is unlikely to have the financial resources to participate as a partner in solar system exploration satellite missions. However, it is vital for the Australian solar system community to be involved on an individual level in the science these missions facilitate by collaborating for example in the data analysis. **This requires the establishment of government-to-government memoranda-of-understanding to enable the formal participation of Australian scientists in overseas spacecraft missions.**

Australian solar physicists work very closely with observations and therefore require continued and immediate open access to data from international solar observatories. This has long been the policy within the international solar community, for example with SOHO. **It is crucial that Australia continue to have direct access to data obtained from future ground- and space-based solar observatories.**

As with all satellite missions, direct participation as a partner in future high-energy, optical and infrared space observatories is very expensive. While such involvement would no doubt be of major scientific importance for Australian astronomers, this Working Group believes that the communities within the country that would benefit from it are too small to justify the very high financial costs. In comparison with for example membership of an ELT project and/or increased share of 8-10m class telescopes, such participation has a lower priority from the perspective of the field of stars and planets. **Instead the Working Group advocates continued access to facilities like Chandra, Swift, SIRTF and future observatories like JWST, GAIA and TPF through collaboration and leveraging on the expertise and analysis skills existing in the country.** It is important that Australian astronomers get involved in the necessary precursor science for some of the major missions in order to be in a position to exploit them fully, as well as becoming involved in the various science teams with guaranteed time.

6.3 Human resources

It is absolutely clear that exploiting the many exciting opportunities opening up in the coming decade in the area of stars and planets also requires a substantial investment in human capital. From the deliberations within the Working Group, and in consultations with the community at large, there is no doubt that the number one problem currently facing Australian astronomers in this field is a severe lack of manpower to carry out the research, both in terms of a shortage of skilled personnel and too little time possible to devote to scientific research.

The Working Group recommends that a certain fraction of all national investments in future observational facilities (national and international) are set aside for theoretical and computational research focussed on the science being performed with these facilities. Such programs are already in place and working very well at for example NASA.

These programs should enable both normal research grants of various sizes as well as dedicated fellowships for early-career researchers.

We recommend that special fellowship programs be instituted in certain key research areas that are of crucial importance for the future of Australian astronomy, but are under-resourced to handle the necessary science. The final choices of these areas should be decided upon after a peer-review process within the community. However, we can readily identify several possible areas within the field of stars and planets. Planetary and extra-solar planetary science is currently undergoing a phenomenal boom in the international community, which however has not yet been fully reflected within the Australian community. This is likely to be one of the key scientific areas in the coming decade and beyond and it is important that Australia does not miss the boat in this respect. There is also a shortage of expertise in high-performance computational fluid dynamics in combination with MHD and/or radiative transfer in Australia. This is very much a central area in contemporary astrophysics as also outlined above (solar/stellar activity, stellar evolution, stellar atmospheres, planet formation etc). Another area which is currently completely missing in Australia today but which would be of great significance is theoretical modelling of massive star evolution and supernovae. In view of the many astronomy areas in Australia that rely on predictions from such calculations, it appears very suitable to develop the necessary expertise in this area.

7 Contributors

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