Planetary Science In Australia

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Summary: Planetary science studies the origin of the solar system and whether life exists on other planets. It has the potential to change the way we view the world and our selves. Planetary science offers a cost effective means for Australia to participate in a prestigious international arena. Space engages the public's imagination and can inspire young people in their choice of careers. Students gain a strong foundation in mathematics, fundamental sciences, and advanced technology, thereby fostering creativity and promoting a culture of innovation. Despite the absence of a national space program, Australian planetary scientists have strong international reputations in cosmochemistry, planetary geology, and planetary geophysics. Many individual Australian scientists are at the forefront of current research into the origin and evolution of the Moon and the early Earth, meteorite impacts, astrobiology, and the evolution of planetary interiors, but they are disadvantaged by a lack of coordination at the national level.

Key words: planetary science, cosmochemistry, planetary geology, planetary geophysics, astrobiology, space program

Introduction

This paper summarises the primary findings and recommendations of the Planetary Science Working Group (PSWG) presented in their final report to the first Australian Space Science Decadal Plan, currently being prepared by the National Committee for Space Science (NCSS). The PSWG report outlined priority research themes for the Australian planetary science community in the coming decade, and it made recommendations for new organizational structures that would benefit the Australian planetary science community. It was submitted to the Decadal Plan Steering Committee in March 2007, following extensive consultation of the Australian scientific community by the PSWG.

In this paper we first present a brief definition of planetary science, and then discuss the national benefits to Australia that could be produced through strong support of planetary science, including education and public outreach. We then summarize current challenges facing the Australian planetary science community and recommendations made by the

PSWG to the NCSS concerning structural changes that would promote the continued development of planetary science within Australia. The main body of the paper is a summary of planetary science themes that are expected to generate major conceptual advances in the coming decade and in which Australian scientists are well placed to contribute at an international level. The bibliography highlights recent Australian contributions rather than attempting a comprehensive review of this immense field.

What is Planetary Science?

Planetary science studies the compositions, physical properties and evolution of the Earth, other planets, moons, asteroids, comets, and other bodies, including their atmospheres, surfaces, interiors, geology, and origins in the primordial solar nebula. We bring samples of other planets and extinct stars into our laboratories, and we map the surfaces and probe the interiors of other planets using data obtained by spacecraft. Our goal is to understand the origin of the Solar System and our place in it.

Planetary science will be one of the most exciting and rapidly expanding frontier research areas of the coming decade. The recent discovery of more than 200 extrasolar planets and the continuing exploration of our Solar System through spacecraft missions and studies of extra-terrestrial materials provides powerful stimuli for understanding the geological and astrophysical processes that create planetary systems and shape the surfaces and interiors of planetary bodies.

Planetary science is inter-disciplinary and international in scope, linking earth scientists, astronomers, physicists, chemists, biologists, engineers, and mathematicians working independently on topics as diverse as the formation of planetary systems, global climate change, the origin of life, and development of new technologies for laboratory analysis and remote sensing. Because Australian planetary scientists typically are employed in related disciplines (e.g. earth science, astronomy, physics) many of the science themes identified here have synergies with strategic research goals articulated by the National Committees for Astronomy and Earth Sciences.

National Benefits to Australia

Planetary science in Australia supports National Research Priority 3, Breakthrough Science and Promoting an Innovation Culture and Economy. National benefits accrue through the production of graduates skilled in mathematics, fundamental science, and technology, and an increase in Australia’s stock of knowledge, a primary driver in the information economy. Both of these outcomes are recognised as vital to the country’s success in using, developing, and adopting new technologies, as well as making informed decisions on the increasing number of science-based issues that confront modern society.

Planetary science research showcases Australian scientific and technical leadership in a field of global interest, thereby enhancing international visibility and national prestige. Space science enjoys widespread public interest and support, and research such as this has the potential to inspire the imagination of young people considering careers in science and technology. The knowledge base among planetary scientists in Australia is vast but somewhat disjointed and less effective than it might be, in part because of lack of coordination at the national level. National support will drive breakthrough science, grow new technologies, and enhance Australia’s international prestige.

The coming decade will see a flotilla of spacecraft missions to Mars, Venus, Mercury the Moon, asteroids, comets and the outer planets by European, Chinese, Indian, and Japanese space agencies as well as NASA. This broadly based international effort has generated renewed enthusiasm for planetary science worldwide. Australia will benefit from participation in these high-profile international endeavours where possible. Research support for planetary science offers one of the most direct and cost effective means by which Australia can contribute to this prestigious international arena.

Planetary science is an ideal vehicle for public outreach and education because it is accessible, rigorous, and timely. Planetary science is especially attractive message because it:

* Engages people's imaginations and their natural curiosity about the world.
* Motivates an aspirational society to compete and achieve at the highest level.
* Connects people with their home planet and their place in it.
* Provides a natural basis for education integrating physical sciences, mathematics, and engineering, bridging scientific disciplines
* Increases the global knowledge base at the macro and micro level.
* Encourages discourse and provides common grounds for action among scientists, educators, industry partners, and policy makers.

Challenges and Recommendations

The PSWG identified a number of significant challenges and structural impediments to effective and efficient involvement of Australian planetary scientists with national and international collaborators. These include (1) the dispersed nature of Australian planetary scientists across the country, (2) the lack of a national focus for planetary science research and mission development, (3) structural restrictions on access to mission data and new technology, (4) emphasis on short-term funding cycles that effectively preclude significant involvement in mission planning. These constraints place artificial limits on the abilities of Australian scientists to function at the highest international level and reduce the potential national benefits that planetary science can deliver.

The Planetary Science Working Group made three recommendations:

1. The NCSS Decadal Plan should support the establishment of a virtual centre in planetary science. Australian planetary scientists are widely distributed across the country and there is currently no central focus for the broad range of planetary science being conducted in Australia. One of the goals of such a virtual centre would be to provide more effective opportunities for collaboration between existing concentrations of planetary scientists in Australia. Such a centre will help build a **critical mass** of Australian planetary scientists, and improve collaborations between Australian planetary scientists, earth scientists, and astronomers. An essential goal is to improve links between science and technology groups within Australia to identify and enhance mission concepts and instrumentation, and leverage interactions with industry and defence.

2. The NCSS Decadal Plan should identify research areas that would benefit from acquisition and development of new instruments, experimental facilities, and data processing capabilities linked to research components of the plan.

3. Appropriate organizations and institutional vehicles for the long term planning, co-ordination and implementation of space science and technology development programmes at the **national level** should be developed to improve the delivery of professional and educational opportunities, and benefits to society.

Key Science Questions

In this section we describe key areas of planetary science in which major progress will be made in the coming decade and in which Australia is well placed to make significant contributions. This section is organized according four broad **science themes** that are expected to generate major conceptual advances in the coming decade: These questions provide a framework within which achievable, high-impact planetary science outcomes over the coming decade have been identified.

1. How and over what timescales did the planets of our Solar System form?
2. How and why do planetary surfaces and atmospheres change over geological time?
3. What is the role of meteorite impacts in planetary evolution?
4. Is there life elsewhere in the Solar System and beyond?

Theme 1: How and over what timescales did planets of the Solar System form?

Nucleosynthesis and stellar contributions to the solar nebula: Precursors to planets

* What was site of formation, initial solar system abundance, and spatial distribution of short-lived radioactive isotopes such as ^{26}Al, ^{60}Fe, and ^{10}Be in the solar nebula?

Significance: These data are necessary to advance our understanding of the astrophysical environment of the inner solar system and timescales of planetary accretion relative to formation other nebular objects to the next level. The initial abundance of ^{60}Fe in the solar system would pinpoint either a supernova or AGB-type star as the source of short-lived radionuclides. This in turn would constrain the relative abundances of other short-lived nuclides from this source, allowing other contributions such as Solar Energetic Particle interactions to be quantified.

Background: Apart from light chemical elements (such as H, He and Li) created during the Big Bang by spallation reactions, the chemical elements of which our solar system is composed were produced principally within the interiors of stars. We know that a variety of exploding stars contributed newly synthesised ejecta to the interstellar molecular cloud from which our solar system was ultimately created. The dust and gas that condensed from the stellar ejecta formed the starting materials for our solar system.

The chemical composition of our solar system was determined by mixing of nuclides synthesized within many different stellar sources over almost 10 billion years. Geochemical studies of primitive meteorites have identified radioactive decay products from about a dozen short-lived (with half-lives ≤100 million years) radionuclides that were active at the earliest stages of nebular condensation. Studies of these short-lived radioactive decay systems in meteorites, terrestrial and lunar samples have established a remarkably detailed high-resolution chronology of some of the key early events such as condensation, accretion and planetary differentiation (Nelson, 2004). Short-lived radionuclides have also been detected in relatively recent (3 million year old) deep-sea sediments by accelerator mass spectrometry. Such radioactive fallout from space may have played a significant role in Earth's mass extinction and climate history.

The origins of these nuclides and their importance as heat sources during planetary accretion and differentiation is a topic of vigorous research. There are three alternative explanations for the existence of short-lived radionuclides in early solar system materials: (i) they were derived from an exploding novae, supernovae or a red giant star in the vicinity and within 2 Ma of formation of our solar system (ii) they were derived by stellar nucleosynthesis reactions within many different stars in the galactic neighborhood at the time of Solar System formation (i.e. Background Uniform Production), (iii) some radionuclides may have been synthesized by spallation interactions with energetic particles from the early and unstable (T-Tauri) sun. The presence of radionuclides with very short half-lives (e.g. ^{41}Ca, which has a half-life of $\sim 10^5$ yrs) requires that a stellar nucleosynthesis event occurred within 2 Ma of the onset of formation of our solar system. The shock waves that originated from this exploding star could have triggered the rapid collapse of a more slowly evolving molecular cloud of interstellar dust and gas nearby, thus initiating the formation of our own Sun and Solar System. The nature of the last stellar source that contaminated our solar system's precursor molecular cloud with freshly synthesized elements may be inferred from the relative abundance of short-lived nuclides in meteorites. Leading contenders are a thermally pulsing Asymptotic Giant Branch star, a Type 1a or Type II supernova, or a Wolf-Rayet star (a massive, short-lived star that ends its life as a supernova; see Nelson, 2004). An additional "galactic uniform production" contribution from earlier nucleosynthesis events may be required to account for abundances of the longer-lived radionuclides, and some of the short-lived nuclides can apparently be produced efficiently by spallation reactions with energetic solar particles.

Nucleosynthesis yields within stellar sites are currently not well constrained, principally due to uncertainties associated with key nuclear reaction rates. Fortunately, yields of several short-lived nuclides and the galactic uniform production rate may be determined by direct observation. Gamma rays are an important by-product of radioactive decay. Recent gamma-ray observations using NASA's RHESSI and ESA's INTEGRAL satellites have facilitated refinement of current quantitative models of stellar nucleosynthesis yields of some short-lived nuclides. Currently only a subset of the meteorite data have been adequately explained. A comprehensive model is needed that identifies the most plausible sources for short-lived nuclides in the solar nebula.

In addition to the isotopic record of extinct radionuclides preserved within meteorites, micron-sized grains that condensed from the gas phase in cooling outflows of stars such as red giants and supernova explosions prior to formation of our solar system have also been identified in primitive meteorites. These pre-solar dust grains formed in the interstellar medium and have made their way into the cloud of gas and dust that eventually formed our Solar System. Although dust-sized particles would have been vaporized as the T-Tauri Sun formed and heated up, a small proportion of these grains survived intact, probably protected inside asteroids that have been sampled as meteorites.

Research at Curtin University and the Australian National University aims to measure the original abundance of extinct and long-lived radionuclides in meteorites and pre-solar grains to constrain the physical environments and extent of mixing in the solar nebula, the stellar sources contributing to the nebula, and the chronology of nebular evolution and planet formation (Amelin, 2005; Kita et al., 2005; Wadhwa et al., 2007). Linking these data to satellite gamma-ray spectrometry on the interstellar medium will enable a better understanding of the astrophysical setting of the early Solar System.

Dynamics of Dusty Plasmas

* What role did dusty plasma environments play in the solar nebula?

Significance: Dusty plasma environments in the solar nebula may provide a unifying perspective on the processes that create planets from dust and gas, the structure of comets, and the behaviour of the Sun.

Background: Dust is a common constituent in many space and astrophysical environments, including molecular clouds, proto-planetary nebulae, stellar outflows, and supernovae explosions. All of these environments contributed in one way or another to the formation of our Solar System, so understanding the formation and behaviour of dust in these environments is fundamental to understanding the origin of the Solar System. The physical and chemical processes that act on cosmic dust and that lead to conversion of dust to planetary bodies will one of the leading research topics in the coming decade. It has the potential to be one of the most synergistic areas of space science, linking cosmochemistry, meteoritics, and astrophysics.

Of specific interest is the fact that dusty space environments often exist in the presence of plasma. Plasmas are conductive assemblies of charged particles, neutrals and fields that exhibit collective effects. Plasmas are the most common form of matter, comprising more than 99% of the visible universe. They permeate the Solar System, interstellar and intergalactic environments. Plasma temperatures and densities range from relatively cool and tenuous (like aurora) to very hot and dense (like the central core of a star). A critical aspect for understanding the behaviour of dust in space environments is the fact that plasmas carry electrical currents and generate magnetic fields.

Low-temperature plasmas in space often contain massive and heavily charged dust grains. Plasmas containing small solid particles ranging in size from nanometers to micrometers are called `dusty plasmas'. Dusty plasmas are common in space, occurring in such diverse environments as interstellar clouds, interplanetary dust, comets, planetary rings, and the Earth's magnetosphere. In addition, the study of the influence of dust in the Earth's ionosphere and atmosphere is an important area for space weather and environmental research. Because of charge redistribution, the presence of dust in a plasma can also strongly affect its collective and transport properties. It is therefore important to investigate the behavior of inhomogeneous dusty plasmas and dusty plasma environments in the early Solar System.

The presence of electrically charged dust in the early solar nebula may have strongly affected almost all aspects of nebular evolution and planetary accretion. For example, dust dynamics and transport, dust clouds and streams, may have controlled the initial stages of agglomeration of nanometer-size dust grains into larger planetesimals, a process that is poorly understood at present. The presence of charged dust also affects plasma collective processes such as wave propagation and plasma instabilities, which must have contributed to mixing and phase separation in the early nebula. The related physical phenomena have relevance across a wide range of space environments, from cometary comae and tails to planetary atmospheres and the asteroid belt, from circumsolar dust rings to the noctilucent clouds in the arctic troposphere. Thus investigations into the physics and chemistry of dusty plasmas may provide keys that unlock current mysteries surrounding such phenomena as the formation of high-temperature nebular objects (e.g., chondrules and refractory inclusions), accretion of planetesimals, and the distribution of dust, gas, and associated chemical species within the nebula.

Certain constituents of primitive meteorites record transient high-temperature environments in the solar nebula. For example, chondrules are round grains of silicate minerals that formed as molten droplets free-floating in space. Chondrules formed by rapid heating (within minutes or less) of solid precursor material to temperatures between 1500°C and 1900°C followed by a cooling within one to several hours. The astrophysical environment and the energy source for chondrule formation are unknown but much current research is directed toward consideration of shock waves in the solar nebula as a possible mechanism for chondrule formation. Another class of high-temperature objects from the early nebula are the calcium-aluminum inclusions (CAIs). These are highly refractory objects composed of oxides and silicates of calcium, aluminum, and titanium that would be among the first phases to condense from a cooling plasma. The mass-dependent fractionation of Mg and Si isotopes in some CAIs are consistent with evaporation or condensation of silicates. In addition, however, many CAI's have peculiar fractionated isotopic compositions of refractory elements such as Ti, Sr, Ba, and Eu that cannot be accounted for by volatility. Alternatively, magnetic separation in stellar outflow environments in plasmas surrounding the young Sun might account for this non-mass dependent isotope fractionation.

These puzzling aspects of chondrules and CAIs may be explicable in terms of dusty plasma environments in the solar nebula. For example, the presence of charged dust causes asymmetries in the plasma that change the behavior of shock waves and the reconnection process. Dust causes long-wavelength oscillations in the magnetic field upstream or downstream of a shock and causes the current filaments to twist and rotate about each other like a giant catherine wheel, or to merge asymmetrically. The extent to which these types of phenomena can explain the observed characteristics of nebular objects such as chondrules and CAIs will require integrated theoretical and experimental studies of the physics and chemistry of plasma environments linked to observations of nebular objects found in primitive meteorites.

Theoretical studies of dusty plasmas are being conducted at The University of Sydney and the Australian National University (Salmeron and Wardle, 2003; Vladimirov and Ostrikov, 2004) but realising the larger potential for significant progress in this area will require new collaborations between Australian space scientists investigating the physics of dusty plasmas and the chemistry of early nebular objects. One mechanism for this collaboration might be the establishment of experimental facilities for investigating the physics and chemistry of dusty plasma systems relevant to the early solar system. New nano-sample handling facilities similar to those used for inter-planetary dust particles will be needed. In addition, new measurements of the ages and isotopic compositions of CAIs and better theoretical models for their formation are needed to establish the nebular environments responsible for mass-dependent and non-mass dependent isotopic fractionations.

The Composition of the Sun

* What is the isotopic composition of oxygen and carbon in the Sun?

Significance: One of the most puzzling aspects of cosmochemistry is the astonishingly wide range of oxygen isotopic compositions observed within primitive meteorites. This may reflect a systematic difference in oxygen isotopic composition of the planets relative to their host star. A significant difference in O-isotopic composition between the Sun and the planets between might arise if there is an isotopic fractionation between dust and gas of the primordial molecular cloud as might be generated by photochemical reactions. In this scenario, the planets would have been sourced entirely from the dust component, whereas the Sun obtains a substantial fraction of its oxygen from carbon monoxide gas. Alternatively, early nebular condensates may have formed in a unique astrophysical environment. Distinguishing between these possibilities and placing better constraints on the processes and physical environment of the solar nebula would significantly improve our understanding of how planetary systems form.

Background: Oxygen is one of the most abundant elements in the solar system, yet components found in meteorites display a 5% range in $^{18}O/^{16}O$ and $^{17}O/^{16}O$. Much of this variability seems to be related to mixing, implying the existence of significant heterogeneity in the early Solar System. Two popular models to explain this variability and predict the bulk composition of the Solar System have been proposed. Because large solid bodies (e.g., asteroids, Moon, Mars, Earth) all have similar ^{16}O abundances, the bulk Solar System may have an oxygen isotopic composition similar to that of the terrestrial planets. Alternatively, early refractory inclusions that have been interpreted as solar condensates have elevated ^{16}O abundance, raising the possibility that the Sun, and therefore the Solar System, has a distinctive ^{16}O-rich composition. The first alternative would require formation of the refractory inclusions in a unique astrophysical environment, whereas the second possibility would require significant processing and heterogeneity in the nebula to create such strong compositional differences between the Sun and the planets. A better understanding of either possibility would significantly improve our understanding of nebular evolution.

A direct measurement of solar compositions may be available from materials that have been exposed to the solar wind where atoms are implanted in to the top 100 nm of mineral grain surfaces. Ion microprobe analyses performed at the Australian National University on natural metal grain exposed to the solar wind on the surface of the Moon have detected oxygen isotopic compositions enriched in ^{17}O and ^{18}O by 5.3 ±0.3% relative to terrestrial oxygen (Ireland et al., 2006). This is in good agreement with a new measurement of the solar photosphere that indicates $\delta^{18}O = +4 \pm 6$ %. The relatively large uncertainties are consistent with a terrestrial or planetary oxygen isotopic composition, but do not support a ^{16}O-rich composition for the Sun. The GENESIS spacecraft mission to the Sun returned small amounts of solar wind implanted on ceramic and metal plates. Despite the hard landing of the spacecraft and subsequent terrestrial contamination of the collector plates, it may still be possible to extract meaningful information using SHRIMP ion microprobe technology. Additional measurements on lunar metal grains and GENESIS collector plates are needed to assess the significance of these initial results.

Accretion and Early Differentiation of Terrestrial Planets

* What were the timescales and processes that created internally structured planets from the dust and gas of the solar nebula?

Significance: Recent results suggest that large-scale planetary processes such as melting and core formation were occurring on asteroids at the same time as the high-temperature nebular events recorded by chondritic meteorites. This is difficult to rationalise within the context of our current understanding of nebular evolution. Geochemical and petrologic studies of igneous rocks from the Moon, Mars, Earth, and differentiated asteroids will advance our understanding of the early dynamics of terrestrial planets, the structure of planetary interiors, and the origins of differentiated bodies in the Solar System. This will provide a direct comparison with timescales for disk evolution estimated by astronomical methods.

Background: Astronomers and planetary scientists now agree that instabilities in the solar nebula lead to rapid growth of km-size planetesimals, probably within 10,000-100,000 years after initial collapse of the precursor molecular cloud. Some of these planetesimals remained cool; chondritic meteorites are samples of these primitive bodies. On other planetesimals, heat liberated by accretion and decay of short-lived radionuclides such as ^{26}Al and ^{60}Fe caused extensive melting and allowed cores of molten iron to separate from their silicate mantles. Basaltic lavas erupted to form a primary crust. The mechanical and thermal effects of collisions among early accreting planetesimals may have contributed to melting, phase separation, and redistribution of volatile elements within the planetesimals

Accretion of rocky planetesimals apparently was synchronous with some of the earliest datable events in the solar nebula as recorded by primitive meteorites. Large-scale melting and internal differentiation of proto-planetary bodies occurred on timescales of 10's of millions of years. This contrasts dramatically with the prevailing view of just a few decades ago in which planets heated slowly over billions of years by accumulation of internal heat from long-lived radioactive decay. Rapid timescales of planet formation implies dynamic accretion probably involving large collisions between protoplanetary bodies and internal heating by short-lived radioactive heat sources.

Ages determined from terrestrial and lunar rocks and meteorites using a diverse array of radioactive decay schemes combined with theoretical models can now provide constraints on the timing of major planetary events including accretion, core formation and crustal growth on the Earth, Moon, Mars, and igneous asteroids (Bennet et al., 2003; Norman et al., 2003). Spurred by analytical advances and the acquisition of more and larger planetary sample suites, an increasingly detailed view of the crustal structures of terrestrial planets (Taylor et al., 2006; Jackson and Carter, 2007) and better constraints on the timing and processes responsible for early planetary differentiation is emerging.

Laboratory studies of planetary materials are needed to establish a high-resolution absolute timescale for the early geological evolution of the inner solar system and the processes responsible for the formation and early differentiation of terrestrial planets. These studies will entail geochemical analysis of radiogenic isotopes, trace element abundances, and mineral compositions of lunar samples, material from key localities representing the early Earth, the Moon, and meteorites from Mars and igneous asteroids (Norman et al., 2006a; Rankenburg et al., 2007). Laboratory facilities needed to conduct these types of studies are relatively well established within Australia. New types of mass spectrometers that will provide greater sensitivity and open new lines of enquiry are likely to become available within the decade and should be sought by departments involved in this type of research.

Theme 2: How and why do planetary surfaces, atmospheres, and climates change over time?

Surface environments

* In what way did the early surface environments and interior processes of Earth and Mars resemble each other, and how and why have the subsequently diverged?

Significance: Early Earth and Mars both appear to share similar dense atmospheres, a methane-CO2 greenhouse, global magnetic field, a hydrologic cycle, abundant volcanism, and intense episodes of impact accretion. The extent of this similarity and when and how the planets diverged to their present different states may highlight common principles of planetary evolution.

Background: Planetary geodynamics is the study of interacting natural processes that operate on and within planets. This type of research integrates surface geology with geophysical perspectives of planetary interiors to characterize structures and processes on regional and global scales. The primary datasets typically are derived from spacecraft observations and, where available, landed instruments.

Much of the research focus over the coming decade will be directed toward a comparison of the structures and evolution of the terrestrial planets Mars, Venus, Earth and the Moon in order to understand the diversity of planetary bodies within our Solar System, their magmatic and tectonic histories, and their atmospheres and climate systems. The scale of investigations ranges from near-surface processes such weathering, hydrothermal alteration, and wind, water and ice erosion and deposition that modify and shape crustal structure, composition and surface morphologies of the planets, to megascopic processes such as mantle convection and meteorite impacts.

An important mechanism for the transfer of heat and mass within solid planets and ultimately to the hydrospheres and atmospheres, is the motion of magma. Volcanic and tectonic activity is a consequence of the release of thermal energy. The various mechanisms that planets adopt for releasing heat are functions of planet size, composition, and distance from the sun. While for Earth plate tectonics and mantle plumes represent efficient heat transport mechanisms, exploration of Mercury, Venus and Mars suggests that there are other thermal mechanisms that should be subtly reflected on the surface of planets by volcanic and tectonic features. Therefore, it is to be expected that the study of terrestrial analogues work may be valuable but not sufficient for understanding how other planets work.

In general, the evolution of planetary atmospheres and climate are strongly coupled to global tectonic styles. Much can be gained from learning how the past and current climates on the other terrestrial planets evolved to their present state, from the release of volcanic gases to the role of biota in the carbon cycle and erosion. Internally generated magnetic fields shelter the surfaces of planets from the solar wind and intense radiation, yet may require recycling of the lithosphere to the core-mantle boundary in order to drive convective currents inside a liquid core strong enough to generate a dynamo. Does this very nature of the continual recycling of the Earth's crust (which exchanges water and gases between the atmosphere and deep interior) provide the materials and energy necessary for developing and sustaining life on the planet? A key aspect for understanding the evolution of other planets over the coming decade will be exploring their surfaces, and placing what we see in the context of geological processes that shaped the planets. The success of the Mars Exploration Rover missions means field geology studies of planetary surfaces can be coupled with remote sensing observations by orbiting spacecraft and the study of spot locations by immobile landers.

Australian research groups have made significant progress on numerical modeling of mantle convection on a planetary scale (Davies, 2006; O'Neill et al., 2007; O'Neill and Lenardic, 2007). Australia also has substantial expertise in remote sensing and mapping, important for defining and exploring relevant surface features of planets (Caprarelli et al., 2007a,b). The combination of these major lines of investigation could provide improved thermal models of the terrestrial planets of the Solar System. This has even broader repercussions that complement cosmochemical studies aimed at constraining the detailed composition of the interior of planets.

The stratigraphy and composition of martian crustal units at the regional and (where possible with lander and rover data) outcrop scales needs to be developed, and testable hypotheses for their formation developed. This will be achieved by harvesting and processing of remote sensing data available from previous and ongoing missions to Mars, as well as direct involvement of Australian scientists in the planning stages of future missions to Mars aimed at collecting specific data to address key science questions.

There is a need in Australia to establish a national hub of planetary data harvesting and processing activities, supported by computer infrastructure, data storage capacity, and personnel straddling modelling, computer processing, physical and geological expertise. A core of such activities already exists at the University of Technology, Sydney, where the procedures to process data from the Mars Odyssey THEMIS (Thermal Emission Imaging System) and Mars Global Surveyor MOC (Mars Orbiter Camera) instruments and to analyse the results using a geographic information system (GIS) are routinely implemented in studies of the surface of Mars (Anania et al., 2007; Caprarelli et al., 2007a,b). Additional support in this area would allow the set up of a facility to establish a national planetary data processing centre, possibly associated with a formal NASA Planetary Data Node in Australia, to increase the number of image processing tools (for example GMT and VICAR) and make them available to other groups in Australia in a user-friendly format that facilitates examination of the data as well as providing expertise to model, process and interpret data.

Several regions of Mars have been investigated at a scale that has been useful to constrain general tenants of Mars genesis and evolution, but that has opened new questions to be addressed by studying features at different scales. This requires design and production of experiments and equipment to be deployed in future missions to the planet. However, the lack of formal collaborative agreements between Australia and the space-faring countries means that Australian scientists find it difficult to participate as principal investigators able to propose experimental designs and produce and test prototypes and final equipment to participate in future missions. Establishment of formal international collaborations between Australia and the agencies operating future planetary science and exploration missions is indispensable to broaden Australian participation in the study of Mars and other planetary bodies. This will produce two outcomes: firstly, Australian scientists will have priority for the examination and analysis of the data; secondly, Australian industry will be directly involved in the design and production of equipment. This will generate and maintain Australian infrastructure and nurture the development of new technological capabilities with the potential for economic returns.

Planetary atmospheres

* Why have the atmospheres of Earth, Mars, Venus, and Titan followed very different evolutionary paths?

Significance: Planetary atmospheres are important because they shape planetary surfaces through erosion and their controlling influence on climate. On Earth, the atmosphere is critically linked to the biosphere because all the important atmospheric gases, with the sole exception of argon, are biologically mediated to some extent. Understanding the evolution of a planet's atmosphere, therefore, provides an important perspective on the history and habitability of a planet.

Background: There are four terrestrial bodies in the Solar System with significant long-lived atmospheres: Venus, Earth, Mars, and Titan. However, each of these atmospheres have distinctive characteristics, reflecting the unique evolution of the planet. The atmospheres of Venus and Mars are mostly carbon dioxide, while those of Earth and Titan are mostly nitrogen. Atmospheric pressures vary widely, from ~90 bar on Venus, to 1 bar on Earth, and 0.07 bar on Mars. The atmosphere of Venus is very acidic with high concentrations of hydrochloric and hydrofluoric acids, and sulfur dioxide that reacts readily with other gases to make sulfuric acid. Earth's atmosphere is predominantly nitrogen but it is distinguished by abundant oxygen, reflecting the presence of photosynthetic life. Titan's nitrogen atmosphere on the other hand is unique for the presence of reduced hydrocarbons. Factors that contribute to the formation and modification of planetary atmospheres include primary contributions from trapped nebular gas, erosion by solar wind, thermal escape, impact, atmospheric cratering, condensation, and chemical reactions.

The surface and lower atmosphere of Venus is largely hidden from direct view by the dense sulphuric acid clouds that extend up to 70km altitude. During the 1980s Australian astronomer David Allen, using the Anglo-Australian Telescope at Siding Spring, discovered a means of seeing through these clouds by observing the nightside of the planet at near-infrared wavelengths. Through "windows" at certain infrared wavelengths it is possible to see thermal radiation from the lower atmosphere, and surface. This makes it possible to study the atmospheric composition and properties in regions that would be hard to reach using in-situ probes because of the extreme temperatures and pressures.

This technique, developed in Australia, is being exploited by the ESA Venus Express spacecraft, now in orbit around Venus. Australian space scientists are also using this technique for continued studies of Venus from the Anglo-Australian Telescope using its new infrared spectrometer IRIS2. Some of the latest results from these ground-based observations of Venus show how infrared observations can be used to probe different levels of the Venus atmosphere, and how they can complement the data obtained by Venus Express (Bailey, 2007b). These data will be used to study the composition of the atmosphere near the surface, the composition and circulation of the cloud layers, and to follow the highly variable oxygen airglow emission, which provides a probe of upper atmosphere chemistry and dynamics.

Australian analogues for planetary surfaces

* How can studies of Australian geological processes (magmatic, sedimentary, hydrothermal, and geomorphological) better inform our understanding of the other terrestrial planets?

Significance: The intelligent extension of uniformitarianism to other planets requires an understanding to the degree to which common and unique processes exist between them. Terrestrial examples can serve both as analogues for extraterrestrial processes, and also as yardsticks against which differences resulting from different compositions, thermal and tectonic regimes, or planetary histories can be measured.

Background: In addition to theoretical studies of global scale physical and chemical processes, there is an opportunity to use Australian environments as natural laboratories to better understand extraterrestrial surfaces, test hypotheses, and develop criteria for recognition of specific processes. For example, the epicratonic basins, landforms and regolith of the Australian interior, such as those near Arkaroola, provide many analogues to the Martian landscape (Clarke *et al.* 2004). The longitudinal dune systems appear to have close parallels on Titan, despite the radical differences in atmospheric density, surface composition, and temperature. The Australian continent has a diverse record of impact cratering and the modification of the craters through hydrothermal alternation, burial, and exhumation (Glikson 1996, Haines 2005). Many of these impact structures have received only cursory study. Finally, Australian geologists have unparalleled expertise in working with early crustal rocks in the Pilbara and Yilgarn cratons.

The topic offers at least three major opportunities: 1) development of new or improved instruments for the collection of *in situ* data (using Australian expertise in spectroscopy, microbeam techniques). 2) Field trials of individual instruments or full-scale prototype rovers in terrestrial analogues settings (such as the FIDO rover trials in the SW United States (Anderson *et al.* 2006) or the NOMAD trials in Chile (Cabrol *et al.* 2001). 3) Framing and testing of hypotheses for field-scale extraterrestrial features with reference to their terrestrial counterparts, especially those features which are particular well developed in Australia such as the results of acid-groundwater systems, (Benison *et al.* 2007), mound springs (Clarke and Stoker 2003, Clarke *et al*. 2007) stable ancient landscape processes (Thomas *et al.* 2005, Pain *et al.* 2007, impact craters (Glikson 1996, Haines 2005), and sief dunes (Bishop 2001)..

Theme 3: What is the role of meteorite and asteroid impacts in planetary evolution?

Early Earth and the Solar System

* Was there a cataclysmic bombardment of the inner solar system about four billion years ago and if so, where did the impactors come from?

*Significance***:** One of the enduring legacies of planetary science is an appreciation of the importance of large-scale collisions or impacts as a fundamental process, especially during the early stages of planetary evolution. An accurate reading of this impact history is important for establishing the significance of large impact events for crust formation and biologic evolution on Earth, absolute timescales of geological events on other planets, and planetary dynamics in the Solar System.

Resolving these questions could answer long-standing problems in planetary science and address current controversies over the source of impacting planetesimal populations that created the large nearside lunar basins. Numerical modelling has raised the possibility that the outer planets Neptune and Uranus either formed late or migrated away from the sun ~500-700 million years after formation of the terrestrial planets. This may have stirred primitive, icy objects from the Kuiper Belt, sending them crashing toward the inner Solar System. In contrast, the size distribution of lunar craters is more consistent with a provenance for the impactors in the inner Solar System, probably the asteroid belt. Distinguishing among these alternatives would provide a better understanding of the evolution of the Solar System after the primary planetary structure was established.

Background: A major insight gained from the study of lunar samples was the realisation that massive impact events occurred considerably later than most models of planetary accretion would have predicted. The age distribution of lunar impact melt rocks and glasses show that a population of large (10-100 km diameter) planetesimals struck the lunar surface at ~3.8-4.0 Ga, some 500-700 million years after initial differentiation of the curst and mantle. The heavily cratered surfaces of Mars and the ages of meteorites from the asteroid belt suggest that a late bombardment at ~3.9 Ga was a general feature of the inner solar system. Where these impactors came from, why they invaded the inner Solar System at this particular time, and their possible influence on the evolution of the terrestrial planets are hot topics in planetary science.

The late heavy bombardment occurred at a time just before the earliest evidence for life on Earth and has important implications for the origin and early evolution of life (Bailey, 2007a). The cataclysm theory leads to much lower total impact rates on the very early Earth than the “steady decline” model. This opens up the possibility that life on Earth could have started very early, and survived through the cataclysm. Alternatively late bombardment may itself have played a role in the origin of life, through delivery of organics to the Earth, creation of temporary environments, or transferring material between planets.

Studies that establish a high-resolution record of the timing of impact events (Norman et al., 2006b) and the provenance of planetesimals traversing the inner Solar System (Norman et al., 2002) are needed. The chronology of early impact events in the inner solar system and the provenance of planetesimals that bombarded the Earth and Moon can be established through geochemical studies of the ages and chemical compositions of lunar impact melt breccias and glasses. The age and composition of the earliest terrestrial crustal rocks and minerals need to be studied to identify whether they contain a signal of the impact record on the early Earth.

Impacts as agents of biogenic and geologic evolution

* What role did impacts play in the long-term evolution of the biosphere and the Australian continent and surface environments?

Significance **:** Improved understanding of the magnitude, rate, and location of impacts onto the Australian continent over the 3.7 billion years of its history will provide better understanding of one particular aspect of the origin and evolution of the early Earth. This is of significance to understanding the formation the compositionally unique terrestrial crust, constraints and niches for Earth's earliest biosphere, and for the development of Archaean metallogenic processes. Improved modelling of the processes occurring in the atmosphere and on the ground during a large impact event would greatly increase our understanding of the evolution of the biosphere, the history of biodiversity, and the risk posed by large, rare events. Two events in particular stand out for further investigation, the Acraman impact event (590 Ma) and the Woodleigh and Picaninny structures (~360 Ma) in South Australia and Western Australia, respectively (Haines 2005). Better understanding of the magnitude and frequency of impact events through the Phanerozoic would also constrain the orbital dynamics of Earth-crossing comets and asteroids.

Background: Large impacts have the potential for significant disruption of the biosphere but the links between major impact events, biosphere disruption, and mass extinction are poorly understood. The best known of such events is the Chicxulub impact, which played a key role in the Cretaceous-Tertiary mass extinction. Other extinctions have been linked to impact events, although links for these are not as clear as for the K-T event.

Impact rates were very high soon after accretion of the planets. They fell away dramatically after ~3.9 Ga but were still significant. The Archaean (2.5-3.7 billion years old) rocks of the Pilbara contain numerous horizons rich in spherulitic glasses that demonstrate major impact events continued to hit the Earth (Hassler *et al.* 2005). These spherule horizons have been used to provide tentative correlations between the Pilbara and Southern African cratons. Although no Archaean impact sites have been identified, the chemistry of the spherules provide constraints on the possible target rocks, which may include lithologies, such as Archaean oceanic crust, no longer present on the Earth's surface. Furthermore, the rate and magnitude of impact events may have constrained the development of the earliest terrestrial organisms.

Detailed geochemical and isotopic studies of Archaean spherule horizons, and field studies to search for new localities in Australia and overseas are needed to produce detailed stratigraphic, sedimentologic, palaeontological, and geochemical investigations of outcrops and drill holes in Australia and overseas across the relevant stratigraphic intervals in the Ediacaran and Devonian periods. Modelling of the environmental consequences of the known impacts against the magnitude of the extinction events would be valuable.

Impact Economics

* What role do impact structures play in modifying groundwater and hydrocarbon flow paths and prospectivity in Australian Phanerozoic sedimentary basins?

*Significance***:** The consequences of large impacts into mechanically weak and/or water saturated sediments is poorly constrained by field studies of terrestrial examples. A better understanding such impacts is important to improve models of the environmental consequences of terrestrial impacts. It is also important for improved understanding of impact processes on Mars, where many impacts appear to have struck targets composed of sedimentary, water saturated material.

Background: The groundwater and hydrocarbon flow paths and prospectivity in Australian Phanerozoic sedimentary basins is of critical importance to present and future hydrocarbon exploration in Australia and to selection of sites for CO_2 sequestration. A number of medium (4 km) to large (120 km) impact structures are known from Australian Phanerozoic sedimentary basins. Examples include Bedout, Talundilly, Woodleigh, Yallalie, Gosses Bluff, Tookoonooka, and Mt Toodinna (Glikson 1996, Haines 2005). Some of these are in basins with known petroleum prospectivity. The impact structures modify fluid flow paths in rocks surrounding the impact site to a distance of at least one diameter away from the impact rim. Changes to porosity, permeability, and subsurface structural and to the thermal history of the target successions can potentially alter petroleum source rocks, reservoirs, and trap potential. However most of these impact sites have been very poorly studied to date. Improved 3D geological and geophysical characterisation of Australian impact craters in basinal successions coupled with improved modelling of impact dynamics and comparison with possible counterparts on Mars are needed.

Impact Risks to Society

* What is the impact risk to Australia?

Significance: The urbanized, networked and industrialized societies of the 21st century are vulnerable to even small impact events (Steel 2001). These include small (Hiroshima-size) to medium (Tunguska-size) air-bursts that occur with frequencies of once a year to once a century, respectively, direct consequences of a land impact, and the indirect consequences such as tsunamis of an ocean impact. There is a significant hazard of small earth-cross bodies causing local to regional scale devastation. Current knowledge of the risk is very limited and early warning minimal. Unlike other natural hazards, the impact risk is one that can be, at least in principle, minimised by direct action. Furthermore, quantification of the risk posed by such events will generate significant data on the composition and orbits of small bodies in near Earth space, with applications to a wide range of astronomical and planetary science questions. Establishment and/or upgrading of long term monitoring ground-based networks of optical and radar systems to track near earth objects. These may be supplemented by microsatellite systems in earth orbit.

Theme 4: Did life arise elsewhere in the Solar System or beyond?

Origin of Life, Habitable Planets, and the Uniqueness of Earth

* Can we sharply define targets for the exploration for life or former life elsewhere in the Solar System?

Significance: The search for life and intelligence beyond Earth is of profound scientific and cultural significance. Knowing whether or not the Earth is representative of a much larger population of habitable worlds beyond the Solar System is a key part of this search.

Background: Of all the questions potentially answerable by planetary science, “Are We Alone” may resonate most deeply with the public. Phrased somewhat less existentially, answering the question of whether life exists elsewhere in the universe is the ultimate goal of astrobiology, which studies the origins, evolution, distribution, and future of life in the universe. This broad field embraces the search for potentially inhabited planets within and beyond our Solar System, including the exploration of Mars and the outer planets, laboratory and field investigations of early life on Earth, and studies of the potential of life to adapt to future challenges, both on Earth and in space. Astrobiology is interdisciplinary, combining planetary science, astronomy, and space exploration technologies with molecular biology, ecology, information science, and related disciplines. The interdisciplinary character of astrobiology requires a comprehensive and inclusive understanding of biological, planetary and cosmic phenomena.

Research is needed to understand the mechanisms by which habitable environments have evolved throughout the Solar System and how the planetary environments have influenced the evolution of life (Bailey, 2007a). Through study of the reciprocal interactions of organisms and their planetary environment we strive to develop an understanding of the biochemical and metabolic machinery that drives the global physical and chemical cycles. We need to understand aspects that seem to make Earth particularly well-suited to support complex life, for example the possible significance of tectonic environment and how it has evolved through time, and the role that delivery of complex organics by primitive bodies may have played in setting the initial conditions that allowed life to begin.

Search for Earth-like planets

* Do early habitats of terrestrial life indicate unique geological or chemical environments are needed for the origin of life?

Significance: Studies of extrasolar planets (exoplanets) over the next decade will help address the fundamental question of whether the Solar System and our own planet have close analogues elsewhere in the Galaxy.

Background: In observations that complement more detailed Solar System analyses, astronomical surveys using different techniques are revealing over 200 gas giants and what appear to be rocky planets in orbit around other stars The surprising overall result from the first decade of exoplanet observations 1995-2005 is the apparent rarity of planetary systems similar to our Solar System. Prior to 1995 we expected to find Solar System analogues with gas-giant Jovian planets in distant orbits, and inner terrestrial planets, all in near-circular orbits. Instead, almost every exoplanet found to date turn out to be gas-giant Jovians in highly eccentric orbits or "hot Jupiters" in extremely close, tidally-circularised orbits. To make matters worse, present information on terrestrial exoplanets is almost non-existent, due to the difficulty of detecting such small, faint and low-mass worlds.

Despite advances made over the past decade, to what extent the Solar System is unique remains very much an open question. This is because observations of extrasolar planets have not been operating long enough to detect gas giant planets in the distant long-period orbits similar to Jupiter and beyond, and as yet, we have little credible information on terrestrial exoplanets.

Over the next decade, observational advances for the first time will enable meaningful comparisons of our Solar System with other planetary systems. Australia currently hosts active extrasolar planet search programs and the nation has the potential to further develop its current expertise and scientific successes in detecting and characterising exoplanets over the next decade. Australia's participation in exoplanet science covers different observational techniques (Bond et al., 2006), as well as some theoretical studies

(Lineweaver and Grether 2003). Radial-velocity measurements are made for the Anglo-Australian Planet Search using the Anglo-Australian Telescope.[1] Transit and microlensing-based searches are in operation (such as the PLANET collaboration), or are in development. These searches are based on infrastructure in place or funded for Siding Spring Observatory in NSW and Mt Canopus Observatory in Tasmania.[2] Innovative development work is also being done on an instrument for the direct detection of exoplanets using polarimetry.[3] Theoretical modelling studies are conducted at several of Australia's universities. [4,5,6]

Over the next decade, progress in Australian exoplanet science will include more ground-based radial velocity survey that will achieve a time base of observations sufficiently long to detect a host of Jupiter-like worlds in Jupiter-like orbits around nearby stars (assuming such planets actually do exist). In addition, developments in hardware and software for radial velocity measurements and transit and microlensing observations should lead to a more comprehensive set of discoveries of terrestrial worlds orbiting nearby and distant stars. These ground-based efforts also pave the way for more detailed space-based studies, and provide the observations on which theoretical advances can be made in understanding the formation and evolution of planetary systems. Solid evidence also should emerge as to the frequency of different types of planets and planetary system architectures. This will help us understand how widespread are planetary systems like the Solar System, and how unique or commonplace are habitable terrestrials like the Earth.

Can we sharply define targets for the exploration for life or former life elsewhere in the Solar System? Although phrased in very general terms this question encompasses many aspects of planetary science but at the same time has a clear goal. It leads to emphases on Mars, Europa, Io, Enceladus and Titan but in one way or another encompasses all objects in the Solar System, the history of the energy output from the Sun, the history of the Earth-Moon system, and more. It links us clearly into the exploration programs of NASA and ESA. It includes instrument development.

Ground-based planet-searching programs in Australia need continuing financial support for their maintenance and development, to garner maximum scientific results from established and developing infrastructure at Siding Spring Observatory and Mt Canopus Observatory. Of particular note is the need to persist with the radial velocity work with the Anglo-Australian Telescope, as the data from this program dates back to 1998, and so offers a unique set of long-term measurements for detecting Jupiter analogues around nearby stars in the southern sky.

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[1] http://www.aao.gov.au/local/www/cgt/planet/aat.html
[2] http://www.phys.unsw.edu.au/astro/research/thesis/MartonHidas.pdf
[3] http://aca.mq.edu.au/People/Bailey.htm
[4] http://www.mso.anu.edu.au/PSI/
[5] http://hubblesite.org/newscenter/newsdesk/archive/releases/2005/10/video/b
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