The Nearby Universe

A report to the National Committee for Astronomy for the Australian Astronomy Decadal Plan 2006-2015

By Working Group 2.2

September 2005

1. Introduction

The remit of this working group was to consider the scientific questions that are likely to be of greatest interest during the next decade within the domain of the "nearby universe (including pulsars)", and the types of investigations and facilities that will be needed to make progress towards answering them. Given that two parallel working groups were considering stars and planets (on the small scale) and distant universe / cosmology (on the large scale), this working group decided to restrict its consideration to the Galaxy and the Local Group, as well as to consider planets in the context of star formation (in particular, the connection to disks). Following the suggestion of the NCA we decided to approach this work by considering what the major questions in the field are today, though we also acknowledge that new fields of investigation that may open up as a result of the introduction of new techniques for observation. Our discussion then produced eight questions of particular interest and significance, and the subsequent writing assignments yielded further consideration to six of these. The questions are listed below and considered further in the pages ahead. We finish by summarising the principal needs that have to be met if progress is to be made towards answering these questions.

2. The Big Questions

The "Big Questions" that the working group analysed were as follows:

- What is the nature of Dark Matter and Dark Energy, and how do they shape the structure of the Universe and individual galaxies?
- When and how did the first luminous objects form in the Universe, and how did they affect their environments?
- What is the life story of the Milky Way galaxy?
- What is the origin and evolution of cosmic magnetism?
- What is the frequency and nature of planetary systems in the Galaxy, and what drives their diversity and habitability?
- What environments can lead to the genesis of life? Could the biogenic molecules that have initiated life on Earth have been seeded from space?

3 The Nearby Universe

3.1 *What is the nature of Dark Matter and Dark Energy and how do they shape the structure of the Universe and individual galaxies?*

One of the great puzzles in modern cosmology is that up to 95% of the Universe apparently consists of dark matter and dark energy, whose physical nature is unknown and which we can only observe indirectly by measuring their effects on baryonic matter (i.e. the stars and gas clouds in the visible universe). Determining the nature of dark matter and dark energy is recognized as an important problem in fundamental physics as well as in astronomy.

The existence of dark matter was first deduced more than twenty years ago when it was found that gas in the outer region of spiral galaxies was rotating faster than expected, implying that these galaxies contained substantial amounts of mass in regions with little or no starlight. Observations of gravitational lensing by galaxy clusters, and of hot X-ray gas around galaxies, confirm that there is more mass in the local universe than can be accounted for by the stars and gas we observe in galaxies.

Over the past decade, microlensing experiments (including the Australian-based MACHO project) have ruled out compact objects (over a wide range in mass) as the main constituent of dark matter in the halo of our own Galaxy. The physical nature of dark matter therefore remains unclear, and if dark matter is made up of new or exotic particles (such as WIMPs, or Weakly Interacting Massive Particles), earth-based particle physics experiments may offer the best hope of working out what it is.

While there is still work to be done in testing possible dark matter candidates (e.g. searches for clumps of cold molecular gas which might plausibly account for some of the dark matter in the Galactic halo), the main focus for Australian astronomers in the next decade is likely to be measurements of the overall distribution of dark matter in nearby galaxies and tests of the Cold Dark Matter (CDM) paradigm for galaxy formation. While the mass distribution in spiral galaxies is already well mapped out by atomic hydrogen studies, far less is known about elliptical galaxies and dwarfs. In these galaxies, the mass distribution can be mapped using planetary nebulae or globular clusters as dynamical tracers. This requires access to 4-8m class optical telescopes with excellent seeing, and ideally with a wide field of view.

Recent observations of distant supernovae imply that the expansion of the universe is speeding up, and “dark energy” has been postulated in order to account for this. There are many possible forms which dark energy could take, including “quintessence” (which behaves like a fluid with negative mass), Einstein's cosmological constant, topological defects in space-time and forms of time-varying energy. More detailed observations are needed to distinguish between competing models but because dark energy (unlike dark matter) is homogeneously distributed through the local universe it is not easily measurable by observations of nearby galaxies. Over the next decade, measurements of very large numbers of standard candles (e.g. supernovae) or standard rods (e.g. galaxy clustering scales) at high redshifts ($z > 1$) are needed, and new wide-field optical and radio facilities have been proposed to tackle this problem.

3.2 When and how did the first luminous objects form in the Universe, and how did they affect their environments?

3.2.1 The search for the oldest, most metal-poor stars

The search for the oldest, least chemically-enriched stars in our Galaxy is, in essence, the search for the first stars that ever formed (or their direct descendants), the so-called "Population III" stars. The oldest stars in our Galaxy have been found by an Australian group, and have only 1/200,000th the solar iron abundance. Debate continues as to their nature, however. Do they correspond to truly first-generation (Population III) stars formed from pristine gas, which then accreted metals via material polluted by the first supernovae? Or are they second-generation (Population II) stars that formed from gas already polluted by supernovae? They may even be Population II or III stars which acquired most of their metals by accretion while wandering the Galactic halo over the past 10 billion years.

What is the spatial distribution of stars that have not been chemically enriched? Currently, there are two stars known with the most extreme low metallicity, measured by the iron to hydrogen ratio, of $[Fe/H]=-5.3$, then an almost total absence of stars up to $[Fe/H] < -4$. Is this gap real? Imaging surveys using special narrow-band filters centred on the calcium absorption line are needed in order to find low-metallicity stars with $[Fe/H] < -3$. Since only one star out of every 50,000 or so in the solar neighbourhood has [Fe/H] lower than this, a vast number of stars needs to be sifted through to find these oldest stars in our Galaxy. Another technique involves proper motion surveys. These are kinematically-biased, and search for high proper-motion stars which originate in the Galactic halo, and thus would have formed earliest in the Galaxy.

The chances of finding true Population III stars in our Galaxy today, with virtually no heavy elements in their stellar atmosphere, are reduced even further if the very lack of such elements to help cool the gas leads to the formation of only extremely massive Population III stars. If a bona fide Population III dwarf star were found, it would put paid to this theory. Its colour and spectrum would help us to model and interpret the re-ionisation of the Universe at redshifts between 6 and 20, and the feedback processes involved in early star formation. Finally, its lithium abundance would help show whether there is a problem with the so-called "concordance cosmology" that has been inferred from other techniques that probe the early universe. For instance, the two lowest-metallicity stars found so far show enhanced carbon, nitrogen and oxygen abundances over that expected in primordial stars, while for one of them the lithium abundance is even less than the predictions from Big Bang nucleosynthesis. How such a star could have destroyed (or be hiding) this primordial element is still a mystery. To make further headway, it is necessary to conduct:

- Imaging surveys in narrow-band (~100Å wide) filters, to select metal-poor stars by their weak calcium and carbon features. Currently, the necessary filters are not uniform enough to provide the high (1%) quality of photometry required. Modest (1-2 m class) telescopes can produce candidates as faint as B~18 magnitudes, which is about the current limit where high signal-to-noise, high-spectral resolution follow-up measurements can be undertaken with the current largest (8-10m class) telescopes that exist.

- Parallel three-dimensional hydrodynamical stellar atmosphere modelling is needed to determine what the elemental abundances should be in such stars.

3.2.2 The Magellanic Clouds as a laboratory for star formation in low-metallicity environments

The Large and Small Magellanic Clouds are satellite galaxies of the Milky Way and are characterised by:

- their far southerly declination (-70°), making them nearly continuously accessible from Australia,
- their low metallicity (25% of solar for the LMC, 10% of solar for the SMC),
- high gas-to-dust ratios, and a high UV ambient flux compared with our Galaxy,
- young, blue populous clusters with 10^4 stars (cf. 100-1000 stars per Galactic open cluster),
- 30 Doradus, the most luminous HII region in the entire Local Group,
- a tightly-defined distance modulus, removing the distance and scale ambiguities inherent in studies of star formation regions within our own Galaxy,
- ongoing interactions with each other, the Milky Way, the Magellanic Stream, and the Bridge, perhaps not unlike the epoch of first star formation if it pre-dated galaxy assembly.

In all these respects, the Magellanic Clouds are the best available local analogues for how star formation may have proceeded in the early, metal-poor universe. Since the last Decadal Review, the Magellanic Clouds have been (or are in the course of being) surveyed, mainly by Australian consortia, across a range of wavelengths, including in atomic and ionized hydrogen, in radio continuum and in carbon monoxide.

One of the key questions being investigated through these surveys is the effect which the high ultraviolet radiation field from the massive, metal-poor stars has on the next generation of star formation. In particular, how is the mass function of molecular clouds affected? While Australian surveys have set out to define the form of this mass function in our own Galaxy, molecular cloud masses in the Magellanic Clouds still need to be measured. Recent innovations, such as on-the-fly mapping and large bandwidth correlators, are the key to making these programs possible. The addition of a focal plane array on the Mopra millimetre telescope would further improve its efficiency and sensitivity, just as the multibeam receiver revolutionised low-frequency astronomy at the Parkes radio telescope.

Ultimately, only Australian access to the Atacama Large Millimetre Array (ALMA) in Chile will enable this work to be completed, by providing spatial resolution in the Magellanic Clouds comparable to current Galactic studies being undertaken with Mopra. This would allow observations to be made that could search for evidence of accretion and mergers between molecular clouds (thought to be the key to the formation of high-mass stars), as well as enabling the measurements needed to understand their chemistry (which drives their cooling and collapse to form stars). Ongoing support is also required for theoretical and experimental astrochemistry investigation and for dynamical modelling of the Magellanic Cloud system, if the observations are to be properly interpreted. Observations of molecular gas in even more metal-poor environments, such as high-redshift radio galaxies, and in the Magellanic Bridge are also of crucial importance in understanding the conditions under which the first stars were born.

3.3 What is the life story of the Milky Way galaxy?

3.3.1 The formation of the Galaxy

Understanding how a large spiral galaxy, like our own Milky Way, arose from the smoothly distributed material of the early universe remains an unsolved problem in astrophysics. Within the favoured model, where motions in the cosmos are dominated by the gravitational attraction of copious quantities of dark matter, the Milky Way grew over time via the steady accretion of smaller systems. Indeed, the fact that the Sagittarius Dwarf galaxy, a satellite of the Milky Way, is being torn apart by the substantial tidal forces of the Milky Way is evidence that this process of galactic cannibalism is still occurring today. While dark matter has played an important role in assembling the mass of the Galaxy, more complex physical processes, such as the cooling and collapse of the gas, and the subsequent formation of stars within it, gave the Milky Way its characteristic and defining form. It has become clear in recent years that these processes leave a significant fossil signature on the observed structure within the Milky Way. The technique of galactic archaeology, where stars are chemically tagged and traced back to their place of birth, will allow us to unravel the formation history of the Milky Way.

Technological advances helped improve our understanding of the formation history of the Milky Way, with detailed numerical simulations providing clues to the smaller-scale physical processes which occur as part of the global star-formation history of the Galaxy. The advent of wide-field photometric and spectroscopic surveys has provided a new observational view of the Milky Way, and revealed its structure and composition in unprecedented detail. While only a first step, these surveys have found surprising and unexpected structure through the halo and in the outer disk of our Galaxy, structure which is not easily explained by current theories. In the coming decade, galactic archaeology will be driven by the confrontation between new extensive surveys of the Milky Way and high-resolution simulations of its formation.

Australia is well placed to make significant advances in these areas, with strong nuclei of leading observational capabilities and theoretical investigations. To maintain this theoretical edge, it is essential to continue to attract leading researchers to the field. This requires the expansion of computational infrastructure to meet the challenge of understanding galaxy formation. Observationally, in the next decade Australia will make use of the AAOmega multifibre spectrograph on the AAT to measure the velocities and abundances of several hundred thousand stars, giving Australia a leading role in this program. Currently, 8-m telescopes are not able to efficiently undertake large-scale galactic surveys, as their instruments have relatively small fields of view. To play a role in unravelling the history of our Galaxy, these facilities will need to expand their observational suite to include wide-field imagers and spectrographs, and so be able to provide detailed kinematics and abundances for the fainter stellar populations in the Milky Way.

An understanding of the life story of the Galaxy must also address the life story of massive stars, since these dominate the energetics of Galactic evolution, extending from strong stellar winds in their early life to massive explosions as supernovae at their end point.

3.3.2 Embryonic massive stars

The scarcity of massive stars, the most luminous and active contributors to the Galactic ecosystem, presents an intriguing set of problems for examination. These most massive stars are confined to the highly-obscured Galactic disk. The more massive a star, the faster its evolution, so in any one phase the numbers that exist are small and one must search the whole Galaxy for them. This is not possible in visible light (owing to obscuration), but radio waves penetrate the dust, and allow us to study the molecular clouds that are the ingredients of star formation. By incredible good fortune, in just the earliest stages of star formation strong molecular masers are generated at radio wavelengths, and provide us with the locations of newly forming massive stars to pinpoint accuracy, their velocities to high precision, and a built-in distance indicator. Besides being the prime tool for discovery of the embryonic massive stars, the cluster of minuscule maser spots around each newly forming star allows magnetic fields and velocity fields to be mapped with exquisite precision. Together with theoretical understanding of the maser process, comparison of different maser species leads to estimates of gas densities and temperatures in the molecular clouds from which the stars are being formed. From such observations we may hope to understand what factors encourage, and what factors inhibit, the star formation process.

So far, we have only scratched the surface of what is possible. The most complete maser studies are currently confined to the brightest examples. The radio telescopes needed for this work operate in the centimetre to millimetre bands, with valuable contributions provided from large dishes and the extensive long baseline interferometric arrays. Australia has these facilities on a modest scale. However, the planned expansion of radio telescopes facilities with the SKA and its intermediate milestones can revolutionise this field of study. It is vital that these front line facilities be built in the southern hemisphere with its unique access to the largest part of our Galaxy.

3.3.3 Stellar endpoints

Much Australian effort is also directed towards studies of stars at the endpoints of their evolution, including supernova remnants, neutron stars and black holes. While observations of supernova remnants have traditionally been centred in the radio band, researchers can now take advantage of two high spatial- and spectral- resolution X-ray observatories, the Chandra and XMM satellites, with anticipated lifetimes extending well into the next decade. The available data measuring thermal conduction, the role of ejecta, and the influence of inhomogeneities within the remnant and in the surrounding interstellar medium, have not been extensively explored. Existing and new data from these observatories, in combination with data from Australian instruments in other wavebands and good local theoretical support on related questions, make the prospects for broad-band supernova remnant studies excellent.

There is significant Australian expertise in X-ray and optical follow-up of transient neutron star and black-hole binaries, as well as in theoretical studies of accretion. Our southern location is an advantage since X-ray binaries are concentrated towards the Galactic centre, and our longitude is also beneficial for round-the-clock observation of transient events. The evolutionary link between millisecond accreting pulsars and recycled millisecond radio pulsars has been cemented over the last three years, with the discovery of five new millisecond X-ray pulsars. Currently two separate classes of objects exist, with half the sources being ultracompact binaries with orbital periods of minutes, and the rest having orbital periods of hours or longer. It is presently unknown how this division relates to the evolutionary pathways for these sources. The prospects for transient detections leading to new discoveries are good, although the Rossi X-ray Timing Explorer, the main workhorse for much of this work, is presently in its tenth year of operations and may not last out the decade. The wide-field instruments on the Integral satellite have proved to be efficient at detecting new transients and it is possible that the Indian Astrosat satellite, to be launched in 2007, will augment and/or replace the capabilities of Rossi. To maintain Australian involvement in this field it is necessary to nurture the existing links with overseas satellite teams, to ensure that this research continues to be feasible in Australia.

In the radio band, Australia promises to continue its premier role in studies of rotation-powered pulsars. The Parkes multibeam instrument, in particular, is likely to significantly expand the known population of pulsars within the Galaxy over the next decade, although not as rapidly as has occurred the past decade due to a number of recent low-latitude surveys. Conversely, since the distribution of millisecond pulsars is generally greater at high latitudes, the fraction of these sources amongst future samples obtained with the Parkes multibeam will likely be greater.

3.4 What is the origin and evolution of cosmic magnetism?

3.4.1 Interstellar magnetism: gas, galaxies and beyond

Understanding the Universe is impossible without understanding magnetic fields. Magnetism is essential for the onset of star formation, directs the large-scale motions of galaxies into turbulence and heat, and is a direct link to processes occurring in the early universe when the first stars and galaxies were formed. Within our own Galaxy, magnetic fields continuously guide the energy of large-scale motions into small-scale fluctuations through magnetohydrodynamic turbulence, and at the same time organise random motions into enormous coherent structures through dynamo processes. These twin mechanisms play a crucial role in particle acceleration, star formation, the propagation of radiation and cosmic rays, and in the heating of the interstellar medium. In spite of their importance, the structure, evolution and origin of cosmic magnetic fields are all still unsolved problems.

Essential to our understanding of astrophysical magnetism are measurements of the structure and geometry of magnetic fields in the Milky Way, in other galaxies, and throughout the overall universe. In our own Galaxy, we still do not understand the turbulent cascade of fluctuations which ultimately dissipates large-scale motions and magnetic fields as heat. Magnetic fields are probably amplified through dynamos, but what produces the cyclonic motion and differential rotation that drives these dynamos, and how fast can magnetic fields be generated? How do magnetic fields regulate starburst activity and overall galaxy evolution? The answers to these questions can provide modellers with powerful new tools to explain the Universe as we see it today.

Magnetism must have also played a crucial role in the formation of the first structures in the Universe. Dynamos and other processes need an original weak magnetic field, which they subsequently amplify and reorganise. Primordial magnetism in the intergalactic medium is thus the likely seed for the magnetic fields seen in present-day stars and galaxies. However, we currently have no constraints on the strength or structure of intergalactic magnetic fields. It is also unclear whether the Universe's magnetism was originally produced by the first black holes, by the earliest generation of stellar dynamos and stellar winds, or through exotic processes at even earlier epochs.

Most of what we know about cosmic magnetic fields comes through the detection of radio waves. Synchrotron emission measures the total field strength, while its polarisation yields the orientation of the regular field in the sky plane and also gives the field's degree of ordering. Faraday rotation of the polarisation vector, resulting from propagation of the radiation through intervening magnetised gas, yields a full three-dimensional view by providing information on the field component along the line of sight. Splitting of spectral lines resulting from the Zeeman effect provides an independent measure of field strength in cold gas clouds. Despite these many complementary sources of information about astrophysical magnetic fields, their measurement is a difficult topic that is still in its infancy and is generally restricted to nearby or bright objects.

Over the next decade, a number of new techniques promise to reveal the “magnetic universe” in greater detail. To study random magnetised fluctuations in interstellar gas, one needs to carry out high sensitivity and wide-field studies of Faraday rotation against diffuse polarised radio background emission. This can provide the first *continuous* description of magnetic fluctuations in the interstellar medium, allowing computations of the power spectrum of the rotation measure in all directions throughout the Galaxy, thus yielding a comprehensive characterisation of magnetic turbulence. A three-dimensional dissection of interstellar magnetism, revealing the shells, filaments and sheets in which ordered magnetic fields are distributed throughout the Galaxy, can be achieved through “rotation measure synthesis”, in which the Fourier transform of polarisation position angle versus wavelength squared directly yields the polarised signal as a function of depth in the interstellar medium. One can also target systems in the foreground of extended polarised screens, to study magnetism in individual galaxies at a range of ages and distances. Rotation measure synthesis of these systems will allow a simultaneous study of both the ordered and tangled components of these galaxies' magnetism, on scales much smaller than can ever be attempted by direct synchrotron imaging. For sources at greater distances, one can make deep polarisation images of the radio sky. Combined with source identifications from optical spectroscopy, the collective sample of sources from such experiments will trace the role of magnetic fields in the evolution of galaxy populations, and will provide an observational underpinning for the very deep polarisation observations ultimately planned for the Square Kilometre Array (SKA). Finally, measurement of the Faraday rotation of tens of thousands of polarised background sources over the entire sky can provide an unprecedented set of plumb-lines for studying the magnetic geometry of the Milky Way and of the local universe.

The facilities needed to address these goals are radio interferometers with wide fields of view (>1°), broad fractional bandwidths (> 20%), and high polarisation purity (< -30dB). Currently no such instruments exist. However, Australia is well placed to develop these capabilities. On a somewhat longer time-scale than covered by the present decadal review, the SKA should easily meet all of these requirements, allowing unprecedented studies of polarisation and Faraday rotation toward millions of faint sources over the entire sky. Indeed, “cosmic magnetism” has been named one of five key SKA science projects.

In anticipation of this eventual capability, many exciting opportunities exist within the next decade. We recommend development of broad bandwidth technologies, full polarimetric response and wide-field capabilities for the existing and planned instruments that will be operational over the next decade, as follows:

- The addition of GHz-bandwidth receivers to complement the forthcoming new correlator on the Australia Telescope Compact Array will provide unprecedented capabilities for rotation measure synthesis experiments in the Galaxy's interstellar medium.
- Mapping the overall magnetic structure of the Milky Way and searching for magnetism in the intergalactic medium both require a survey for extragalactic polarised sources over the entire sky. The SKA Molonglo Prototype (SKAMP) could

be the ideal instrument for such an effort, if outfitted with a broad-band dual-polarisation line feed and a new reflector mesh.
- The search for magnetic fields in the intergalactic medium also requires distance determinations to a significant fraction of the polarised extragalactic sources detected. This requires multi-band photometry of optical counterparts, as could be obtained with the ANU SkyMapper telescope.
- A sensitive wide-field low-frequency radio interferometer, as is being currently considered in the form of the Low Frequency Demonstrator (LFD) at Mileura, can provide an incredibly detailed view of magnetic fields in local interstellar gas.
- Finally, deep polarisation surveys of individual galaxies and of the extragalactic sky can be undertaken with the high sensitivity and polarisation purity of the planned Extended New Technology Demonstrator (xNTD).

These activities all will provide the scientific and engineering studies needed to ensure that the SKA has full polarimetric capability, and will allow Australian astronomers to accomplish the science goals described here and also to fully capitalise on new opportunities as the window to the magnetic universe finally begins to open.

3.5 What is the frequency and nature of planetary systems in the Galaxy, and what drives their diversity and habitability?

The detection and study of planetary systems and proto-planetary disks around nearby stars is an exciting research area and one that is growing rapidly. There are several niche topics within this area where Australian telescopes can have a large impact. Other nations will be committing extensive resources to this field, particularly for space-based observatories, so it is unrealistic to expect Australia to dominate it. International collaborations are the best way to leverage the geographic advantage of our facilities.

Planetary systems around other stars can be studied in various ways. The coming decade will certainly lead to rapid advances in all of these. Over the past ten years this new branch of astrophysics has come from a situation of having hardly any data, to the present startling diversity of planetary systems and circumstellar disks. The physical, chemical, and ultimately biological questions raised by this rich new observational field are attracting wide theoretical interest. In the next decade the subject will mature, with observational advances guiding theoretical efforts to establish new paradigms for the formation and evolution of planetary systems.

The first direct detection of circumstellar disks came from Infra-Red Astronomy Satellite (IRAS) observations of Beta Pictoris, Alpha Lyrae, and other nearby, bright stars. More recent mid-infrared studies with Infrared Space Observatory (ISO) and the Spitzer Space Telescope have revealed many similar debris disks, evidently the remains of proto-planetary disks (“proplyds”) long after the planetary formation process has ended. Proplyds themselves have been studied in the infrared and optical with the Hubble Space Telescope (HST), and they will be prime targets for the Atacama Large Millimetre Array (ALMA). Large ground-based optical telescopes can detect the spectroscopic signatures of the gas in proplyds, but for imaging it has been necessary to use space-based telescopes in the optical and infrared to achieve the required resolution (< 1”). The James Webb Space Telescope (JWST) and the proposed ground-based extremely-large optical telescopes (ELTs) will advance this field greatly in the next decade.

The molecular gas in the disks can also be detected through observations in the millimetre regime. The recent upgrade of the ATCA to operate at 3mm wavelength has made it the only millimetre interferometer in the southern hemisphere and one of the most sensitive instruments of its type in the world. It will play a major role in the next five years in making high-resolution observations of the molecular gas in disks in nearby low-mass star forming regions. Information on the molecular gas content for disks of different ages can be used to determine temperatures, densities and chemical compositions, and hence to infer the evolution of the disk. Our knowledge of how planetary systems form from disks is currently poor, and such observations will constitute a major advance and provide constraints for theoretical modelling. Similar observations are possible with northern millimetre interferometers, but the ATCA has an important role to play in the Southern Hemisphere in undertaking preliminary observations for follow-up by ALMA in Chile.

Habitable planetary systems are not likely to occur around high-mass stars, which have relatively short lifetimes of the order of millions of years (rather than billions of years for stars like the Sun). How these high-mass stars form remains very much an open question. Once a star reaches a mass approximately eight times greater than that of our Sun, the pressure from the intense radiation it produces is sufficient to halt the further accretion of material. However, many stars with masses in excess of eight solar masses are observed in our Galaxy, so there must be some means to create them. One possibility is that they form through coalescence, or alternatively accretion may proceed through a thick or flared disk. To date, few disks have been detected around high-mass stars and their detection and study at radio and millimetre wavelengths is another area where Australia can reasonably expect to play a role through observations with the ATCA and through long baseline interferometry with the Long Baseline Array.

Planets, as opposed to disks, have been detected primarily by their gravitational perturbations to the motion of their companion stars. This was first detected in pulsar timing observations and many more examples have since been found through high precision optical spectroscopy. Several of these have been confirmed by photometric detection of the planetary transit in front of the companion star. A different photometric technique that shows great promise is the detection of planets through their gravitational lens amplification of the light from a background star. The advantage of this last method is that it is does not have the strong bias toward high mass planets at small distances from their companion stars that is present in the Doppler techniques. It is therefore more likely to detect earth-like, habitable planets.

The next decade will bring ambitious developments in space interferometers designed to detect terrestrial planets and spectroscopic signatures of life on them. The front-runners in this effort are NASA’s Terrestrial Planet Finder and ESA’s Darwin telescopes. These are ambitious and costly missions involving constellations of spacecraft with very challenging requirements for station-keeping in order to do optical interferometry of planetary systems. Results from these missions may be more than ten years away, meanwhile ground-based searches will continue. The pace of detection of planetary systems has been accelerating, so that over the next ten years several hundred or even thousands more systems may be detected. The microlensing techniques may even reveal planets similar to those in our solar system.

Australia’s role in these efforts will necessarily concentrate on specific areas where we have a distinct advantage. Generally, nations which have large amounts of telescope time on the largest optical telescopes will dominate the Doppler technique searches, limiting Australia’s role in extending the detections to lower masses. The microlensing method requires a network of observatories that can undertake continuous photometry over periods of a few days. For Southern Hemisphere objects Australia is well positioned to contribute to these networks. For example, the Hobart telescope at Mt. Canopus and the Perth Observatory are major players in the PLANET consortium. In the radio, Australia dominates pulsar searches and timing studies in the southern hemisphere, so further detection of planets around pulsars constitutes a favourable niche. If an infrared telescope were constructed on a high altitude Antarctic site this could become a leader in the searches for proplyds and debris disks in the mid-infrared (5 to 30μm wavelengths).

3.6 What environments can lead to the genesis of life? Could the biogenic molecules that have initiated life on Earth have been seeded from space?

Few questions challenge the imagination more than the question of whether there is life in the Universe, other than the Earth. Could there be, or was there once, life elsewhere in the Solar System? Does life also exist elsewhere in the Galaxy? If so, could life on Earth have been seeded from the interstellar environment? Could there then be common genetic traits across the Galaxy? In the coming decade humanity can go beyond simply raising such questions, and begin the quest in earnest of conducting experiments which try to answer them.

To do so, we need to address the question of what environments life might exist in, and how these environments come to be, in order that we can determine what it is best to look for. A natural starting point for the search is our own Earth – how might we find similar objects, whose surfaces are covered in liquid water and lie within a habitable zone around another star? However, that may be too confining for the search of parameter space. As the discovery of liquid methane on Titan shows, liquids other than water may be abundant elsewhere on a planetary surface, and exist within a hydrocarbon environment. While life may require a fluid medium to sustain the transport of materials to it, and the waste from it, perhaps that medium need not only be water?

These environments on planets and satellites have themselves formed from processes that take place within the dusty disks that surround protostars, molecular cloud cores which have gravitationally collapsed within cold clouds of gas. The extended surface areas of the disks and clouds make their detection and dissection easier than that of the planets which they ultimately produce. The clouds themselves are also rich in molecules, with a complex organic chemistry underway – taking place on the surfaces of dust grains and in the gas phase as the protostar heats up and evaporates material from the grain mantles. Do biogenic molecules exist inside these clouds? Species such as acetic acid, glycoaldehyde (a sugar), ethylene glycol (anti-freeze) have been found in some sources, and even glycine (the simplest amino acid) found in a few meteorites (and controversially claimed to have been detected in the interstellar medium). Do chiral molecules exist and if so what is the balance between right-handed and left-handed versions of the molecules? Can these molecules then seed planets with the organic material needed for the precursors to life? If so, are the origins of life similar across the Galaxy?

These questions may all be addressed through precise observations at infrared, millimetre and centimetre wavelengths. They demand high spatial resolution, to resolve structures on scales of a few arcseconds to milliarcseconds, high dynamic range to simultaneously measure faint objects adjacent to bright stars, and large collecting areas to provide the sensitivity to discern the necessarily weak emission signatures.

Protoplanetary disks will emit radiation that may be detected from thermal infrared wavelengths ($\lambda > 3\mu$m) to centimetre bands ($\lambda \sim 1$cm), depending on the temperature and size of the regions and the column density of the emitting material. With angular extents of up to several arcseconds for objects within 100pc of the Sun, millimetre and sub-millimetre interferometers with kilometre-sized baselines will be capable of resolving the extent of cold ($T < 100$K) disks. Such observations will provide the first indications of the presence of incipient protoplanetary disks within star forming cores. In the warm central regions of solar system-sized disks, mid-infrared observations with current 8m-class telescopes will be able to detect the emission from arcsecond-sized regions, but be insufficient to resolve more than the most basic structures. Planets themselves will not be discernable, but it is possible that gaps carved out of the disk due to presence of forming planets may be seen. Antarctic telescopes with diameters of 2m or larger would be particularly potent for such studies, combining the high sensitivity resulting from the low background with the high angular resolution facilitated by the stable atmosphere. Telescopes with diameters of at least 30m, or mid-infrared interferometers with similar baselines, will be needed to resolve structure on a 0.1" scale (e.g. at Jupiter-orbit scale for a system 50pc away). 100m baselines or apertures will be needed to examine structure on the AU-scale. Spectrometers operating across the windows from 8 to 30μm will provide information on the physical characteristics of the grain material, in particular with the ability to distinguish between crystalline and amorphous material, as might be expected if the inner portions of disks undergo substantive heating and processing during the planetary formation phase.

The emission from the inner regions of disks will likely be optically thick at infrared wavelengths, but optically thin in the millimetre and centimetre bands. Radio observations are therefore needed to measure the amount of material present. For instance, for a disk of mass $0.1M_{\odot}$ and radius 10AU, the emission would be optically thin for $\nu < 10$ GHz. Furthermore, to resolve structure in the inner AU of a source 100pc away requires a spatial resolution of 0.01", equivalent to a 500km baseline at 10 GHz, and also a collecting area of $\sim 10^6$ m^2 for the emission to be detectable. Furthermore, a critical but poorly understood aspect of planetary formation involves the growth of dust grains, in particular how dust grains of size a few millimetres grow to sizes of a few metres, without smashing themselves apart in collisions (when they reach larger sizes gravity can then take over the accretion process). To examine this phenomena, observations at wavelengths comparable to the grain size are needed; i.e. in the millimetre and centimetre regimes.

To study the organic chemistry inside a molecular cloud it is necessary to measure the plethora of spectral lines emitted from the molecules across the sub-millimetre and millimetre regimes. In the sub-millimetre, higher rotational levels are evident, arising from warmer (and therefore smaller) regions, closest to the protostellar objects where, presumably, the 'hot core' chemistry is also being driven. The more complex, and therefore rarer, the molecule, the more emission lines are present, a facet of the complexity of the partition function. The lowest energy lines are also shifted towards the low frequency end of the millimetre spectrum the heavier the molecule; i.e. in the 3, 7 and 12mm bands. To be sure of a detecting a rare species, many lines from it need to be measured to distinguish it from the line 'jungle' of all the species present. Wide correlator bandpasses are essential to achieve this. The ability to observe across the entire mm-windows simultaneously, with spectral resolutions sufficient to resolve down to thermal line widths, would greatly facilitate the search for biogenic molecules, allowing a complete inventory of the species present in many protostellar environments to be undertaken. Current correlators have around 10,000 channels, but million channel devices would be needed to provide such a capability. Such investigations can readily be undertaken using single dish millimetre-wave telescopes. In addition, interferometry further helps the process of identification, by providing validation, or otherwise, that any candidate lines found all arise from the same region of space, within the beam of the single dish telescope.

4. The Big Questions and their Solutions

In summary, the Nearby Universe working group has posed six key scientific questions within this scientific domain. It has then considered what developments are needed in order to allow them to be better addressed in the coming decade. A synopsis of the questions, and the facilities and support needed in order to search for their answers, is given below.

Question: What is the nature of Dark Matter and Dark Energy and how do they shape the structure of the Universe and individual galaxies?

- Solution requires measurement of the distribution of dark matter in nearby galaxies, using optical spectroscopy on 4-8m class telescopes to determine the dynamical motion of tracers, such as planetary nebulae, which can be used to determine the overall mass distribution in these galaxies. Wide fields and good seeing especially important.
- Solution requires the detection and quantification of “standard candles” that can be used as distance estimators to probe the expansion of the Universe and so examine how the expansion rate may be accelerating at the largest distances. Utilises wide-field optical and radio telescopes to detect candidates and then yield their luminosity and recession speeds.

Question: When and how did the first luminous objects form in the Universe and how did they effect their environments?

- Solution requires wide-field, optical photometric surveys using 1-2m class telescopes to uncover prospective chemically-poor stars as candidates for the oldest stars.
- Solution involves high signal to noise, high spectral resolution optical measurements with 8-m class telescopes of candidate stars to determine their chemical abundances.
- Solution requires wide-field proper motion studies to identify halo stars.
- Solution requires numerical simulations of stellar atmospheres to predict spectral features and their strengths in low-metallicity stars.
- Solution requires a comparative study of the Milky Way's companion galaxies, the Large and Small Magellanic Clouds, which provide an analogue of a chemically poor environment in which the first star formation occurred. This can be pursued through millimetre-wave molecular line observations of these galaxy's molecular cloud complexes in order to characterise their star formation activity. Requires 3mm focal plane array on Australian telescopes and access to ALMA.
- Solution requires development of theoretical and laboratory expertise astrochemistry.

Question: What is the life story of the Milky Way galaxy?

- Solution requires uncovering fossil record of the Galactic history through wide-field spectroscopic and multi-colour photometric measurements of stars distributed through the Galaxy, to determine their ages, streaming motions and origins. Requires development of wide-field capabilities on 8-m class telescopes.
- Solution requires theoretical modelling of galaxy interactions and computational infrastructure to support intensive numerical simulations.
- Solution involves the study of massive star formation, the dominant process underway in the Galaxy today. Requires millimetre and sub-millimetre interferometry to characterise the environment of the gas and the dust in the cores where massive star

formation occurs, and centimetre-band interferometry to survey and characterise the maser emission (e.g. from OH, CH_3OH and H_2O masers) that signposts the active sites of star formation.
- Solution requires study of stars at the endpoints of their evolution in X-ray wavelengths to probe their interaction and feedback with the interstellar medium. Requires access to X-ray satellites to achieve.
- Solution requires radio band surveys to determine the distribution and characteristics of pulsars as end points of stellar evolution.

Question: What is the origin and evolution of cosmic magnetism?
- Solution requires measurements of rotation measures and polarisation in the radio bands, using centimetre-band and metre-band interferometers with wide fields of view (>1°), wide fractional bandwidths (>20%) and high polarization purity (< -30dB), as well as collecting areas of up to 10^6 m^2.
- Solution requires multi-colour photometry of optical counterparts to distant radio galaxies to determine their distances.

Question: What is the frequency and nature of planetary systems in the Galaxy, and what drives their diversity and habitability?
- Solution requires observing planetary disks, requiring high spatial resolution imaging in the mid-infrared (facilitated by Antarctic telescopes), and interferometric imaging in the millimetre and sub-millimetre (facilitated by ATCA and ALMA), to resolve their structure and composition.
- Solution requires high precision spectroscopy and photometry, at optical wavelengths, of stellar systems to detect presence, and determine characteristics, of planets, through the techniques of orbital Doppler-shifts, transits and micro-lensing.

Question: What environments can lead to the genesis of life? Could the biogenic molecules that have initiated life on Earth have been seeded from space?
- Solution requires observing protoplanetary disks, requiring interferometric measurements to resolve their structure and composition in mid-infrared, sub-millimetre and millimetre (and possibly short-centimetre) wavebands, as would be facilitated by Antarctic IR telescopes, the ATCA, ALMA and SKA.
- Solution requires spectroscopic measurement to identify dust grain features in the protostellar disks, from 8-30μm. Requires high spectral and spatial resolution spectrometers on Antarctic and 8m-class IR telescopes.
- Solution requires sub-millimetre and millimetre (from 3-12 mm) searches for emission lines from organic (and biogenic) molecules in the interstellar medium. Requires ultra-wide-band correlators (fractional bandwidths > 20%) to recognise fingerprints from such molecules.

5. Recommendations

The following are recurring themes through this discussion of facilities needed to support research programs into the Big Questions identified in this report.

- In the optical and infrared: access to telescopes from 1 to 8m in diameter, in Australia, on excellent temperate sites, and proposed in Antarctica, equipped with frontline instrumentation such as wide-field cameras and high resolution spectrographs.
- In the radio: access to single dish telescopes and interferometers in Australia, operating from ~1–100 GHz, equipped with frontline instrumentation such as wide bandpass correlators and focal plane arrays.
- Access to the new generation of sub-millimetre facilities now under construction overseas, in particular the Atacama Large Millimetre Array (ALMA) in Chile.
- Access to low frequency (< 1 GHz) interferometers, as for instance envisaged with the proposed Low Frequency Demonstrator.
- Access to wide-field of view, high sensitivity radio interferometers, with both high fractional bandwidth and high polarization purity, as envisaged through the proposed technology development route leading from the Extended New Technology Demonstrator to the Square Kilometre Array.
- Access to X-ray satellites to complement Australian capability in optical and radio bands.
- A vibrant community of theoreticians, whose work complements and stimulates that undertaken with these observational facilities.

6. Contributors

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Australian Astronomy Decadal Plan, 2006-2015
Working Group 2.2 Appendix:
Pulsars

1 Introduction

The topic of pulsar astronomy falls between the areas of both WG2.2 (The Nearby Universe) and WG2,3 (Stars and Planets). This report on the pulsar science was therefore prepared by Baerbel Koribalski and Lister Staveley-Smith, with input from those listed in Section 7 below.

2 The Big Question

The "Big Question" identified by Australian pulsar researchers was

- Can a complete theory of gravity be tested using pulsars and black holes?

This is also one of the key science questions driving the design of the Square Kilometre Array (SKA).

3 Pulsars in the decade 2006-2015

3.1 Introduction

Australian astronomers and facilities have been pivotal in pulsar astronomy since the 1970s. Over half the known pulsars have been discovered at the Parkes 64m radio telescope. These include the exciting double pulsar PSR J0737-3039 (Lyne et al. 2004), which is crucial in testing relativistic theories of gravity, and many millisecond pulsars that are nature's most accurate clocks. Parkes also holds the record for the most precise timing of millisecond pulsars because of advances in instrumentation and the generous amount of time available on the Parkes 64m telescope.

Over the next decade, Australia's lead in pulsar astronomy is threatened by facilities such as the 100m Green Bank Telescope (GBT), which can see large parts of the southern sky with three to four times better sensitivity than the Parkes telescope, and the Arecibo multibeam system which will detect more than 1000 pulsars in the northern Galactic plane. The power of the GBT has been shown with the discovery of 21 new millisecond pulsars (MSPs) in the globular cluster Terzan 5 (Ransom et al. 2005), confirming fundamental predictions of globular cluster and binary system evolution (13 of the new MSPs are in binaries). Only three pulsars were previously known in Terzan 5.

Pulsar astronomy is largely driven by survey successes and follow-up timing observations. The Parkes 21cm multibeam surveys are largely complete and we are near the theoretical limits in sensitivity with a 64m dish for timing. To remain at the forefront, Australia needs to look at facilities that can increase sensitivity in both pulsar searches and timing. A large field-of-view is required for pulsar surveys, whereas very high sensitivity (collecting area) is needed for the follow-up pulsar timing.

For survey work, a telescope like the xNTD is ideal in theory, but in practice the gains may be are limited by massive computing problems. If surveys using interferometers are restricted to incoherently adding the outputs from each telescope, then a system such as the proposed SKA Pathfinder would be needed to make the next leap forwards.

The ultimate goal of a complete Galactic census of all pulsars, detecting all pulsars in globular clusters, timing pulsars in the Galactic Centre, and detection of significant numbers of extra-galactic pulsars probably has to await completion of the SKA.

3.2 Gravity wave detection using a pulsar timing array

Pulsars can be used as interstellar gravity wave detectors due to their incredible spin stability. Timing an array of about 20 millisecond pulsars to an accuracy of 100ns would place severe limits on the cosmological background of gravitational waves, and possibly make the first direct detection. At present, sensitivities are marginal and we may require a five to ten times increase in sensitivity to achieve this goal. The ideal instrument would be the equivalent of a 200m dish with a cooled receiver and about 500 MHz of bandwidth at 1.5-2 GHz. This sort of sensitivity is higher than that envisaged for the xNTD concept but is less than that likely to be available from the SKA pathfinder system, and could be operational at the end of the coming decade.

3.3. Gravity wave emission from pulsars

Direct upper limits on the amplitude of gravitational waves from 28 isolated pulsars have recently been set from data obtained with the LIGO interferometric detector. The upper limits to the strain are as low as a few times 10^{-24} (Abbott et al 2004).

Direct detection of gravitational waves from binary pulsars and/or burst oscillation sources is also possible (Bildsten 1998). The prediction is that gravitational wave emission limits the spin rate of accreting neutron stars in binaries. These sources offer good prospects for detection as gravitational wave sources since they are the only candidate persistent sources in the few-hundred Hz frequency range with known orbital and rotational periods. Australia has a good record and convenient southern location for optical followup of these transient sources, which can be critical for good positions to permit a correct timing solution. Observationally we can also contribute with photometric/spectroscopic observations to complete the sample of burst oscillation sources with known orbital periods.

3.4 Tests of gravity in a pulsar-black hole system

Binary pulsars are and will remain the only way to test the predictions made by general relativity (GR) or competing theories of gravity in the strong-field limit (Kramer et al 2004). Previous pulsar tests have shown that GR's prediction for gravitational quadrupole radiation is correct to within the measurement uncertainties, which are currently better than 1% (Weisberg & Taylor 2003). The largest strong-field effects, however, are only encountered to date when studying pulsars in compact binary systems. Prime examples are double-neutron star systems such as the famous PSR B1913+16 system (Hulse & Taylor 1974) or the first discovered double pulsar PSR J0737-3039 (Lyne et al. 2004). Hence, we should aim to find pulsars in compact orbits around a massive companion, i.e. a stellar or even massive black hole. The consequences for timing a pulsar around a black hole have been studied in detail by Wex & Kopeikin (1999), who showed that the study of orbital dynamics allows us to use the orbiting pulsar to probe the properties of the rotating black hole.

Testing of GR phenomena such as frame-dragging is also possible using the quasi-periodic X-ray oscillations in neutron-star/black binaries (Markovic & Lamb 1998). These systems already have extensive phenomenological study, so the primary opportunity for progress may be in theoretical studies, in which Australia has a good record and moderate level of investment.

Prime survey targets for radio pulsars around black hole companions would be the innermost regions of our Galaxy and in globular clusters (Kramer et al 2004). Discovering pulsars in the Galactic Centre requires high sensitivity (SKA Pathfinder) and high observing frequencies (up to 15 GHz) to combat the effects of interstellar scattering (Cordes & Lazio 1997). Timing of pulsars near the supermassive black hole at the centre of our Galaxy will be very important for dynamical studies.

An instrument like the SKA Pathfinder would also enable the detection of many more eccentric binary systems in globular clusters, like those recently detected in Terzan 5. It would increase the chances of finding millisecond pulsars orbiting black holes and double millisecond pulsars, which are fantastic laboratories for testing general relativity to even higher precision than PSR J0737-3039.

4. Contributors

This report was compiled from contributions from Matthew Bailes, Duncan Galloway, Simon Johnston, Andrew Melatos, Paulo Freire and Michael Kramer, and edited by Baerbel Koribalski and Lister Staveley-Smith.

References

Abbott, B. et al., 2004, gr-qc/0410007.
Bildsten, L. 1998, ApJ, 501, 89.
Cordes, J.M. & Lazio, T.J.W. 1997, ApJ, 475, 557.
Hulse, R.A. & Taylor, J.H. 1974, ApJ, 191, 59.
Kramer, Backer, Cordes, Lazio, Stappers & Johnston 2004 `Strong-Field Tests of Gravity Using Pulsars and Black Holes', in "Science with the SKA", eds. C. Carilli & S. Rawlings, New Astronomy Reviews 48, 993.
Lyne A. et al. 2004, Science 303, 1153.
Markovic, D. & Lamb, F.K. 1998, ApJ, 507, 316.
Ransom, S.M. et al. 2005, Science 307, 892.
Weisberg, J.M. & Taylor, J.H. 2003, Radio Pulsars, ASP Conference Proceedings, Vol. 302, held 26-29 August 2002, Chania, Crete, Greece, ed. M. Bailes, D.J. Nice & S.E. Thorsett (San Francisco: Astronomical Society of the Pacific).
Wex, N. & Kopeikin, S.M. 1999, ApJ, 514, 388.