Cosmology and the High Redshift Universe

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

By Working Group 2.1

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1. Introduction

This document was produced in response to a request by the *National Committee for Astronomy* (NCA) for input into the *Australian Astronomy Decadal Plan*. The authors are Working Group 2.1 of the decadal review process (see Section 7). We were asked to describe the science case for cosmology and the high redshift Universe in the next decade (and beyond), and to outline the resources needed to reach these science goals. This document is broken down into two parts. First, we describe a number of science areas that will be important in the next decade. The most crucial of these are the following three:

1. Dark energy, dark matter and the equation of state of the Universe.
2. The first luminous objects and the "epoch of reionization".
3. The formation and evolution of galaxies.

As well as these three areas, there are a number of other related areas where significant advances will be made in the next decade.

In this document, we first give an overview of the each of these science areas (sections 2 - 5) and then discuss the top-priority resources that will be required to enable Australian scientists to be competitive in these areas in the coming decade (section 6).

2. Dark energy and the equation of state of the Universe

The recent discovery that the expansion rate of the universe is accelerating is perhaps the most startling breakthrough in science since Hubble's demonstration of the expansion itself. Such was the surprise at this acceleration that a leading theorist declared that the data were simply wrong. However, the evidence that the cosmos is accelerating has now strengthened to the point where very few cosmologists doubt its accuracy.

Within our current understanding of the Universe, explaining the observed acceleration requires radically new physics. Either gravity must be fundamentally different from the description put forward by Einstein; or a new form of matter, with a *negative* pressure, must dominate the cosmic energy budget – the so-called *dark energy*. Both these possibilities would have a profound impact on our understanding of the Universe and physics at the deepest levels. The simplest possibility is that the dark energy is the cosmological constant postulated by Einstein, but if this is not the case then we will need entirely new physics. In other words, dark energy will force us to take physics beyond the currently-accepted “standard model”.

To determine the properties of dark energy will require measurements significantly beyond the current state-of-the-art surveys. These have given us very little information about the nature of dark energy other than in its existence. In particular, we wish to know the equation of state of the dark energy. This is conveniently parameterised as *w*, the ratio of its pressure to its energy density. The simplest form of dark energy is the cosmological constant (a modification to gravity) which corresponds to a constant value of *w*=-1. Our challenge is to perform surveys that will discover the value of *w* and hence the nature of dark energy. It is important to use more than one method in this investigation, not only to minimise systematic effects but also to probe dark energy with a range of different physics.

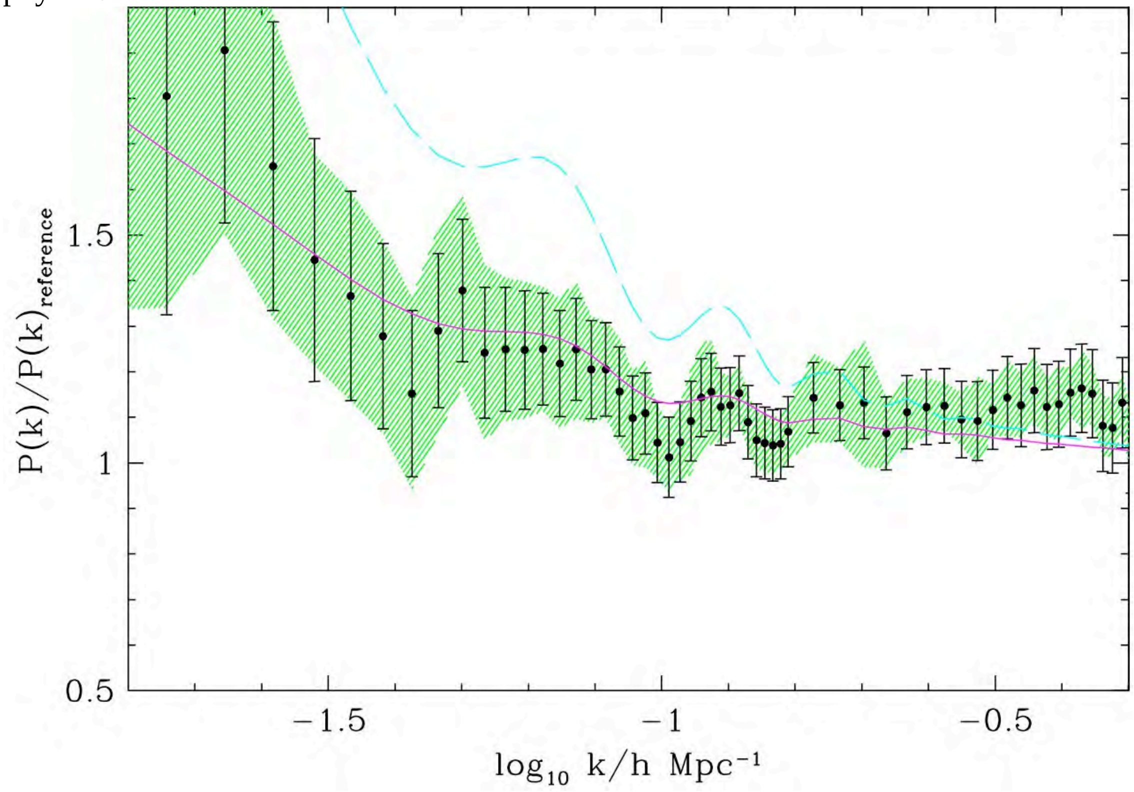

Figure 1. *The power spectrum of galaxies from the 2dF Galaxy Redshift Survey (2dFGRS), divided by a smooth reference power spectrum (Cole et al. 2005). These fluctuations in the power spectrum reveal the acoustic signature in the data. The data points are correlated but show evidence for oscillations to match the theory. The cyan line is the best-fit theory; the magenta line is this best-fit theory convolved by the window function of the 2dFGRS.*

2.1 Optical galaxy surveys

2.1.1 Scientific motivation

The clustering of galaxies on large scales preserves the fossil record of the growth of structure in the early universe. This information can be measured in large galaxy surveys and used to investigate the properties of dark energy. In particular the galaxy distribution features an imprint of acoustic oscillations dating from the epoch of recombination. These oscillations have a characteristic length of 150 Mpc, determined to high accuracy by existing observations of the Cosmic Microwave Background. The oscillations act as a standard ruler - if we observe them looking back to different epochs (redshifts) in the universe, then we can measure the expansion of the universe as a function of time to high precision and thus constrain the properties of the dark energy equation of state.

In January 2005 two independent groups reported the first detection of acoustic oscillations, using data from the Anglo-Australian 2dF Galaxy Redshift Survey (2dFGRS) and the US Sloan Digital Sky Survey (SDSS). The 2dFGRS result is shown in Figure 1. These detections alone do not provide strong constraints on the behaviour of *w*, as they are low-precision detections at relatively recent epochs. To fully constrain *w*, it is necessary to obtain more accurate measurements of the acoustic oscillations at much earlier epochs. This will require much larger, more distant galaxy samples.

2.1.2 Australia's strengths

Australia has an extremely strong record in the application of optical galaxy studies to cosmology, including the two-dimensional APM galaxy survey (Loveday et al. 1992), which was one of the first major studies of the large-scale distribution of galaxies, and the three-dimensional 2dF Galaxy Redshift Survey (Colless et al. 2001), which jointly reported the first detection of the acoustic oscillation signal. Australian scientists were directly involved in both these projects and the latter was led from Australia. More recently, Australia is jointly leading the SDSS-2dF Luminous Red Galaxy survey. This international collaboration combines the best of each of the two previous surveys to study a sample of much more distant galaxies. It draws distant targets from the SDSS imaging data and measures their distances with the Australian-built and operated 2dF spectrograph. This project is an example of the large collaborative project needed to measure dark energy. These projects rely on multi-object optical fibre spectroscopy, a technology in which currently Australia leads the world.

2.1.3 Future requirements

In order to place reasonable constraints on the dark energy equation of state, future surveys will need to measure the acoustic scale length to a precision of about 1-2 per cent at early epochs. The first opportunity to do this will be with the AAOmega spectrograph on the AAT, which will come into operation in 2006. This will make possible surveys of up to 500,000 galaxies out to redshifts as high as $z{\sim}1$ by targeting luminous red galaxies or star-forming emission-line galaxies, and should constraining the acoustic scale length to a precision of ~2-3 per cent. Such a large observing program would require ~200-300 nights of telescope time. Probing to higher redshifts and greater precision will require new instrumentation. A 1 per cent measurement looking back half the age of the universe (to a redshift of z=1) would require 2 million galaxies, and looking back 80% of the age (z=3) would require 600,000 galaxies. To measure the distances to these galaxies efficiently, we would need to use a wide-field multi-object spectrograph on an 8-10m class telescope. Australia currently has a leading role in design work for the Gemini Telescope's Wide Field Multi-object Spectrograph (WFMOS), which is one of the best prospects for measuring the evolution of the equation of state. Even with the capacity of WFMOS the two surveys combined would require 215 clear nights, or 1 year allowing for weather. This would typically be scheduled over a 3-year period and based on previous projects it would require a minimum of 4 full time plus another 8 part-time research staff to process and analyse the data over a 4-year period.

2.2 Dark Energy with Supernovae

In 1998, an Australian-led team used type Ia supernovae to demonstrate that the Universe was accelerating, and therefore must be dominated by some form of Dark Energy. Australia's supernova focus over the next several years will be to gather the best-possible ground-based SN Ia sample in order to constrain the dark energy equation of state parameter to +/-0.1. This effort is requiring a significant amount of Australia's Gemini-N and South time (50 hours per year), as well as time on the CTIO Blanco telescope, Keck, and the VLT, provided by US/European/Chilean collaborators. While there are efforts overseas to put together even larger samples of SN Ia with new instruments such as PanStarrs and the Dark Energy Camera, it is unlikely that these projects will include significant Australian involvement. Finally, around 2015, it is possible that the US Joint Dark Energy Mission (JDEM) Satellite will undertake a more comprehensive experiment using SN Ia. Australia is currently involved in this mission at a low to moderate level.

2.3 Dark Energy with radio surveys

2.3.1 Scientific Motivation

Tentative detections of the signature of dark energy have already been found via the correlation of radio source counts and fluctuations in the Cosmic Microwave Background (CMB). Radio sources are excellent tracers of the high redshift Universe, and large radio surveys are able to probe the surface mass density of the Universe with high uniformity. As CMB photons propagate through large potential wells, they suffer a net gravitational redshift in the presence of dark energy (the Integrated Sachs-Wolfe, or ISW, effect). The amount of correlation between the fluctuations in the radio source counts and the CMB temperature is a measure of the equation of state of the dark energy. It is proposed to undertake such a radio survey with the xNTD.

Large radio telescopes, such as the SKA pathfinder, or the SKA itself will be more sensitive to dark energy and will be able to probe the change of the equation of state with redshift, a key component in understanding the nature of dark energy. This will be done by undertaking large HI surveys to measure the three-dimensional power spectrum, thereby studying the radial and transverse expansion of the acoustic peaks since the epoch of recombination. Abdalla & Rawlings (2005) calculate that an error of 1% in the w-parameter will be possible at z=1.5 with the SKA.

Since HI observations allow rotation curves to be measured, the evolution of the velocity function of galaxy halos is easily measured. Such observations begin to be possible at moderate redshifts with the xNTD, but will require the greater sensitivity of the SKA pathfinder and SKA to reach z=1. Being a simple volume measure, the velocity function probes the geometrical expansion of the Universe, and therefore the dark energy content, using a quantity that is much less sensitive to evolution that HI mass or optical luminosity functions (Newman & Davis 2000).

2.3.2 Future Requirements

Radio telescopes with large fields of view and large collecting areas operating at relatively low frequencies are required. The frequency of the redshifted 21cm line lies in the range 350 to 1420 MHz for redshifts up to 3. The xNTD is the first step, and will allow a straightforward integral measure of dark energy via the ISW effect. More accurate and powerful measures will require an SKA "pathfinder" telescope with an area of 10% or so of the SKA.

3. The first luminous objects & the epoch of reionization

3.1.1 Scientific motivation

Observations of the Cosmic Microwave Background (CMB) imply that the very early universe was smooth and simple with a neutral baryonic component. This is in contrast to the universe we observe today which is complex, inhomogeneous and has an intergalactic medium (IGM) that is highly ionized. This motivates two of the major questions in extragalactic astronomy: (i) when and where did the first luminous sources form? (ii) When and how did these sources re-ionize the neutral hydrogen and helium throughout the Universe?

Optical telescopes cannot directly observe the universe at times earlier than the Epoch of Reionization (EoR), because in order for the light to be redshifted into the optical band it must have been emitted in the UV where it would have been completely absorbed by trace quantities of neutral hydrogen in the IGM. This forces observations to be made at longer wavelengths (e.g. infrared or radio wavelengths).

Most of the current observations probing the reionization epoch are absorption-line studies of the highest redshift quasars. Before reionization, quasars were embedded in a diffuse IGM that was partially neutral and prevented transmission of flux immediately blueward of the Ly-α transition at the quasar redshift. The resulting absorption trough is referred to as the Gunn-Peterson (1965) trough. Seven quasars exhibiting a Gunn-Peterson trough have recently been discovered with redshifts beyond 6, placing the end of reionization epoch around that time. However, the Wilkinson Microwave Anisotropy Probe (WMAP) has found a large optical depth to Thomson scattering of CMB photons by free electrons in the IGM, implying significant reionization at a much higher redshift (z~10 to 20). The combination of these two observations presents a challenge to our conception of the process of reionization. It suggests that reionization was an extended process, in contradiction to the previously-held view that the universe underwent a fairly rapid transition from an neutral to an ionised IGM.

We now believe that the first generation of stars, rather than an early population of quasars, caused the majority of reionization. However, even with next generation telescopes, the direct detection of the first generation of stars (the so-called Population III stars) in the early Universe will be a challenge. The best chance of detecting these is by the observation of gamma-ray bursts (GRBs) and supernovae at high redshift. Much theoretical work is also required in order to better understand how population III stars form and evolve.

3.1.2 Australia’s strengths

Australian astronomers have extensive experience in large radio surveys and are currently playing a major role in the development of new EoR experiments (e.g. LFD and others). There is also considerable theoretical expertise in understanding the observational signature of reionization.

3.1.3 Future requirements

Propelled by recent observations, the question of how the neutral IGM was reionized has become one of the most important topics in modern cosmology. Our best hope of solving this problem lies in new direct observations of the pre-reionization IGM. In the next decade, low-frequency radio telescopes will carry out new surveys of the redshifted 21cm line of neutral hydrogen in both emission and absorption, with the aim of tracing the three-dimensional structure of the neutral IGM before reionization. The detection of the epoch of reionization will provide our first glimpse of when and where the first stars and galaxies were formed. Several of the planned observational EoR projects have substantial Australian involvement.

The Low-Frequency Demonstrator (LFD) is part of the Mileura Wide-Field Array Project, which is a collaboration between the ATNF and US and Australian universities. The LFD will operate in the largely-unexplored frequency range between 80 and 300MHz. When deployed in a radio-quiet zone in Western Australia, the LFD should be capable of detecting the EoR both through the observation of the edge of the Gunn-Peterson trough along the line-of-sight to high redshift quasars, and through the detection of the 3-dimensional power-spectrum of fluctuations in emission from neutral hydrogen. A complementary, smaller scale experiment to detect the frequency at which emission from the neutral IGM disappears (the global step of the EoR) by using concentric log-spiral antennae (Subramanian, Ekers et al.) will also be deployed on the Western Australian site. Australian astronomers are also amongst those providing theoretical input into this evolving area, and the SkyMapper Telescope (Schmidt et al.), should discover tens of new, very high redshift quasars which can be targeted by the LFD.

Development of low-frequency radio telescopes and the LFD in particular will take Australian astronomers into new technological and scientific areas. The computing requirements for the LFD are roughly an order of magnitude larger than are required by current astronomical facilities, and the required computing technology for an LFD is currently under development. Realization of the potential of the new generation of low-frequency telescopes will require substantial resources to develop skills within, and to expand the existing community, in addition to Australia's existing engineering and scientific strength.

Supernovae and GRBs will enable the "direct" detection of the earliest luminous sources, but this will also require new facilities. Supernovae from population III stars will be detectable to z~10 or higher with an Extremely Large Telescope (ELT) with an aperture of 20m or greater. The James Webb Space Telescope (JWST) will also be able to make direct detections of globular clusters forming at z~10-20. New space missions, in particular GLAST and SWIFT, will discover many new GRBs including some which are expected to be in the redshift range of interest for EoR studies. These GRBs will require intensive follow-up observations (with quick response) at infrared and radio wavelengths, using 8m class telescopes and ELT/SKA for the most distant sources. Direct detections of star formation at high redshift are complementary to the 'Galactic archaeology' studies outlined in the report by WG 2.2.

Support needs to be given to theoretical research to further our understanding of star formation in the early Universe. This is expected to be very different to star formation observed locally, due to the unique physical conditions at early epochs (e.g. essentially zero heavy elements).

4. Understanding the formation and evolution of galaxies

One of the key goals of modern cosmology is to determine how and when galaxies form. Much progress has been made in the last decade with a combination of major surveys to moderate depth and narrower deep samples to probe high redshifts. The global star formation rate is now crudely traced to z~5-6, but although we have a general theoretical framework in the cold dark matter (CDM) model, our understanding of how galaxies are built up over cosmic time remains very limited. Several outstanding issues remain and these include (i) how and when does gas turn into stars? (ii) How are the morphology and luminosity distribution of galaxies seen locally created? (iii) What is the impact of super-massive black holes on their host galaxies, and how do they co-evolve? These and other critical issues that address the formation of galaxies are discussed below.

4.1 The morphological and luminosity distribution of galaxies

4.1.1 Scientific Motivation

A decade ago (c.1995), relatively few galaxies had been observed with optical telescopes at distances beyond what we now consider the nearby ($z < 0.5$) universe. In general, the only optical data which could be obtained for such galaxies was a simple, and often grossly incorrect, total flux measurement. With the advent of the Hubble Space Telescope, (which provided high-resolution optical imaging), and 8m class telescopes (which could measure reliable redshifts and chemical signatures), we are now able to detect and measure the sizes and metallicities of galaxies out to redshifts of z~6, when the Universe was less than 10% of its current age. New classes of galaxies (Lyman-Break, Lyman-α clouds, extremely red objects (EROs), "train-wrecks", SCUBA sources etc.) have been detected and defined with these new telescopes, and with an associated wave of new technology, typified by near-IR and sub-mm detectors. This has led to multi-wavelength studies of galaxies, which emphasise that galaxies are made not only of stars distributed in distinct structural patterns, but of dust, gas and plasma as well.

As almost all astrophysical processes occur inside galaxies, the topic of galaxy formation and evolution is synonymous with the evolution of the baryons from the smooth primordial (light element) distribution at the time of the recombination of hydrogen atoms through to the rich diversity of galaxies, stars, planets, gas, dust and plasma that we see today. Over the next decade the mission of a significant fraction of the astronomical community will be to fully explore this diversity and complexity from the nearby Universe to the furthest reaches. This will require higher-resolution, larger aperture, wider-field and multi-wavelength facilities and in particular the near-IR, far-IR and sub-mm wavelengths. Two distinct modes of science are required:

1. The survey approach, to quantify the classes, components (bulge, disk, halo etc) and constituents (stars, gas, dust, plasma etc) of galaxies over a wide range in redshift.

2. A detailed dissection of representative case studies, to improve our understanding of the specific physical processes at work.

The combination of these two approaches should lead to a detailed understanding of galaxies, galaxy evolution and galaxy formation, and is an entirely realistic goal for the next decade.

4.1.2 Australia's Strengths and Future Requirements

Australia has always been a major player in optical survey astronomy, as typified by the Schmidt Telescope, the Macho Project and the Two-degree Field Galaxy Redshift Survey (2dFGRS). In terms of the first ('survey') approach to galaxy evolution, definitive studies of the space density of galaxies have been carried out at Mt Stromlo Observatory through the Mt Stromlo-APM survey (Loveday et al. 1992), the 2dFGRS (Norberg et al. 2002) and most recently the Millennium Galaxy Catalogue (Driver et al 2005). With the advent of AAOmega on the AAT, Australia is well-placed to continue a leading role in this area. A key complement to AAOmega is the high-resolution optical and near-IR imaging (not possible from within Australian)which will be carried out by facilities such as UKIRT, VISTA, Subaru, Magellan and the LSST. Hence Australian access to a wide-field high-resolution optical/IR imaging/spectroscopic system should be seen as a priority. The most obvious facility is Subaru, which may also host the planned WFMOS wide-field spectrograph.

More worrying is Australia's ability to engage in the second ('detailed dissection') approach, which requires significant time and access to the upcoming very large optical/IR facilities (8m telescopes and ELTs) and the JWST. Although Australia has the scientific expertise (Webster, Couch, Lewis, Hopkins etc.) to pursue such goals, Australian access to the necessary facilities are limited and likely to impede Australian contributions to this key area. The two main areas to focus on are significant access to large-telescope facilities (i.e. more 8metre and ELT access) and ensuring access and ease of access to space missions (e.g., Spitzer, Galex, HST, XMM etc).

The imminent demise of the Hubble Space Telescope (HST) poses a risk that many avenues of exploration in this field will be shut off due to the resolution limits of ground-based telescopes (which can only achieve comparable resolution by using adaptive optics techniques over very small fields of view). Recent developments in Antarctic astronomy (Burton et al. 2005) suggest that a 2m-class telescope located in Antarctica could emulate many of the capabilities of the HST. The UNSW-led PILOT project potentially offers access to high-resolution optical imaging at a resolution comparable to HST, which could allow continuation of the direct study of galaxy morphologies. Tantalizing evidence has been presented (Burton et al. 2005) to suggest that, due to reduction in the thermal background level, an Antarctic 2m telescope could be at least as sensitive, at near/mid IR wavelengths, as an 8m facility on a prime site such as Mauna Kea. While such an instrument would not be able to compete in terms of absolute spatial resolution, the survey power, due to the coupling of high sensitivity, excellent resolution, and huge (in comparison) field of view, would make much of the science proposed for the original HST/NIMCOS instrument finally accessible. One could study in detail the rest frame optical properties of galaxies, and their evolution, out to redshifts as high as z=1.

4.2 The stellar populations of galaxies

4.2.1 Scientific Motivation

The large SDSS (120,000 galaxies) and 2dFGRS (250,000 galaxies) surveys have raised some intriguing results concerning the stellar populations of galaxies in different environments. For example, the distribution of galaxies is bimodal, with the relative proportions varying with environment (Blanton et al. 2005). Surprisingly, galaxy masses and star formation histories appear to be more closely tied to environment than to galaxy morphology. Star formation is suppressed on group-like local density scales (Lewis et al. 2002). The physical mechanisms and timescales which produce these trends are yet to be fully understood. Further progress requires detailed stellar population properties, e.g. to reproduce the bimodal galaxy colours in terms of age and metallicity, probe star formation histories on Gyr timescales, and to trace mass (via velocity dispersions) rather than light and study the phenomenon of `galaxy downsizing'. Large samples are required to probe issue such as environmental trends, relations between different galaxy types and masses, transition galaxies (such as E+As which represent a few percent of the galaxy population; Blake et al. 2004) etc. Many important aspects, such as alpha-element ratios (which provide star formation timescale information) have barely been probed. Bell et al. (2004) recently concluded that the relative importance of gaseous vs. stellar galaxy assembly was a *completely open* question. Globular clusters, which trace major star formation episodes, offer a unique probe in this respect (current work suggests that dissipationless processes are dominant).

4.2.2 Australia's Strengths

There has been much work in Australia on many aspects of stellar populations in nearby and more distant galaxies. Two of Australia's most cited researchers (Freeman and Couch) work in this general area. Australia was given further international exposure by the 2dF Galaxy Redshift Survey (led by Colless). Although focused on large-scale structure, it also returned valuable data on the galaxies themselves (e.g. Lewis et al. 2002). The 2dFGRS was able to explore *current* star formation rates via Hα equivalent widths, but was not well suited to a more detailed stellar population analysis. The 6dF Galaxy Survey (6dFGS), which is currently in progress, will do much better in this regard as provides both high S/N and wide wavelength coverage, suitable for a detailed stellar population analyses over a range of galactic environments. Over the last few years, a number of extragalactic globular cluster systems have been age-dated providing further constraints on the host galaxy evolution (led by Forbes).

With a large 6dF sample, one can fully test the hierarchical model predictions for galaxy age (e.g. Kauffmann & Charlot 1996) and alpha-element ratios with environment (Thomas & Kauffmann 1999), examine differences between cluster and field S0 galaxies and hence cluster transformation processes, probe the star formation history of E vs S0 galaxies, trace the age-mass-metallicity hyperplane for galaxy sub-samples (Trager et al. 2000), probe differences in galaxy populations in virialised vs non-viralised systems (Miles et al. 2004) and examine suggestions of carbon abundance anomalies in cluster galaxies (Sanchez-Blazquez et al. 2003). We can form a local-Universe `environmental Madau plot', i.e. define the star formation history of the $0<z<0.1$ Universe. For the first time, we will be able to explore the issue of non-solar abundance ratios for a variety of elements (eg Mg, N and C appear super-solar while Ca is sub-solar) in a large sample. Such ratios give star-formation timescales and further clues to chemical enrichment histories. The red spectra cover the Ca triplet, which is especially good for velocity dispersion measures, and a large sample of Ca triplet indices may help solve the current puzzles surrounding this index (Michielsen et al. 2003).

4.2.3 Future Requirements

Telescopes/Instruments:

In the immediate future the AAT+AAOmega can provide large numbers of galaxy spectra sufficient for stellar population analysis. Gemini + GMOS can provide similar data for more distant galaxies, or for nearby galaxies probing beyond the central galaxy regions to large radii. However, Australia's telescope share is a major limitation to a detailed study. Telescope time is also a limitation for stellar population studies of extragalactic globular clusters. A larger field-of-view than offered by Gemini + GMOS is also desirable -- thus a wide field multi-object spectrograph on a 20m class telescope is required.

Manpower:

The 6dFGS and AAOmega surveys will generate large volumes of data. These can be relatively easily reduced by pipeline software. However, the key to extracting the most scientific return from these surveys will be having the expertise in Australia for the analysis. Thus researchers are needed with the necessary skills in stellar population models and spectral analysis.

4.3 Evolution of gas in galaxies

4.3.1 Scientific motivation

Understanding the formation and evolution of galaxies is one of the leading challenges in theoretical cosmology. The hierarchical paradigm for the formation of cosmic structure predicts that galaxies are gradually assembled over time through the merger of successive clumps of cold dark matter (CDM). Measurements of the size and mass of galaxies at different cosmic epochs therefore provide crucial tests for theories of galaxy formation. Since the large-scale distribution of neutral hydrogen directly traces the distribution of dense halos of dark matter, whereas the light emitted by a galaxy is largely decoupled from the mass distribution, measurements of the size and mass of the neutral gas in galaxies provides the most direct test of the 'mass assembly history of the universe' predicted by hierarchical models.

To develop a complete picture of the evolution of galaxies, it is necessary to study the way in which cool gas accretes into galaxies from other potential wells and from the intergalactic medium, and to study the expulsion of gas from galaxies via winds and stripping processes. At this point, the evolution of cool gas in galaxies is only probed by the damped Lyman-alpha absorber population. These provide only a crude measure of the gas density of the Universe at redshifts above 1.6. However, interpretation is ambiguous and does not seem to match the massive changes in the star formation rates observed at infrared and radio wavelengths.

A far more powerful measure of the gas content of galaxies is the brightness of the 21cm emission line, which provides a direct measurement of the mass of neutral hydrogen (HI). However, the HI emission lines is very weak and the sensitivity and sky coverage of existing radio telescopes is such that only a handful of detections have so far been made for galaxies above redshift $z=0.1$. The SKA technology demonstrators currently under construction (including SKAMP and xNTD in Australia, the Allen Telescope Array in the USA and the upgraded Westerbork telescope in Europe) will be able to carry out HI emission-line surveys of large numbers of galaxies to at least $z\sim0.3$, as well as probing HI in more distant systems through wide-field HI absorption surveys to $z\sim1$ or higher. The SKA Pathfinder planned for later this decade, with a collecting area 10-20% that of SKA, will be able to detect HI in emission from normal galaxies out to $z\sim1$. Thus the next decade is likely to see great progress in our knowledge of the neutral gas content of distant galaxies.

Observations of radio-frequency molecular lines, particularly CO, trace gas associated with star formation in galaxies. The CO lines are strong compared to HI, and can already be observed to very high redshift (the CO 1-0 transition was recently observed in emission at $z>6$), providing a powerful independent probe of the cosmic star-formation history. Over the next decade, the ALMA telescope is likely to revolutionise our understanding of molecular gas and star formation in high-redshift galaxies.

4.3.2 Australia's strengths

Australia has a strong track record in HI surveys, and an Australian team used the Parkes multibeam receiver to carry out the first blind HI survey of the local universe (HIPASS). The Australia Telescope Compact Array (ATCA) has mapped the detailed kinematics of many southern galaxies in HI, as well as producing detailed HI mosaics of both Magellanic Clouds. Since its recent high-frequency upgrade the ATCA has carried out key studies of the redshifted CO 1-0 line in galaxies at $z>3$, including the first detection of CO in a galaxy at $z>5$. Various theoretical groups (in particular at Swinburne) have strengths in modelling and simulating galaxy formation (including gas physics) at high redshift.

4.3.3 Future requirements

To compare with models, we require radio telescopes capable of detecting the HI content of galaxies well above $z=0.1$. This requires radio telescopes with both large collecting area and wide field of view. Strong evolution is predicted in all galaxy formation models (Pei & Fall 1999; Baugh et al 2004), so observations at moderate redshifts of 0.2 will already be a powerful discriminator between different models. The two SKA technology demonstrators currently being built in Australia, the University of Sydney SKA Molonglo Prototype (SKAMP) and CSIRO's Extended New Technology Demonstrator (xNTD), have complementary strengths in this area (SKAMP has a larger collecting area, enabling it to detect normal galaxies in emission out to $z=0.3$-0.4; xNTD will have a wider field of view, allowing it to carry out an all-sky HI survey to $z=0.2$). Access to these two facilities will allow Australian astronomers to remain at the forefront of HI studies over the next 5-10 years. Access to the international SKA pathfinder telescope (around 2012) will extend this work to $z\sim1$, and is also essential.

For molecular-line work (e.g. CO), access to ALMA (and later SKA) is essential. The ATCA, with its new wide-band correlator and coverage of the 15-50 GHz spectral region, will still have a key role to play since ALMA will only work above 100 GHz. SKA (and pre-SKA pathfinder telescopes working at 100-300 MHz) may be able to detect $z>6$ HI in absorption against background radio galaxies, though the surface density of radio galaxies at these redshifts is currently unknown. Access to current and particularly next generation X-ray satellites (XEUS and Constellation-X) will be important in studying the hot gas content of galaxies and the formation of galaxy clusters.

Continued support for theoretical work involving modelling and simulation of high redshift galaxy formation is critical to proper interpretation of observations.

4.4 Dark matter in galaxies

4.4.1 Scientific motivation

We know that about 90% of the gravitating mass of most galaxies is in a dark form. It is not gas or dead stars, but the nature of this dark matter remains unknown and is one of the great astronomical problems of our time. Astronomers suspect that this dark matter is made up of some kind of subatomic particle left over from the big bang, and its physical nature may be revealed in the physics laboratory rather than by astronomical techniques.

Dark matter is pivotal in our current theories of galaxy formation. The dark matter appears to form a halo around the luminous galaxy, and these halos of larger galaxies are believed to be built up through the merging of smaller galaxies. We would like to study the properties of galaxies at early times in the universe, to see this process of halo-building taking place. We would also like to study the detailed structure of the inner parts of dark halos at different times, because the inner parts of halos provide an acute diagnostic for the various processes that go on during galaxy formation.

The Tully-Fisher law is another diagnostic of how galaxies are built up. The law relates the speed of rotation of a galaxy (defined by its dark halo) to the brightness of the galaxy (defined by its stars). One of the key problems in galaxy formation is to know how the slope and zero-point of the Tully-Fisher law change with time or redshift. The redshift interval of interest for galaxy building is from $z = 0.5$ to about 2.5.

4.4.2 Future requirements

The observational requirements for this kind of work are two-dimensional spectroscopy at optical, near infrared and radio wavelengths. Large collecting areas are needed, because the galaxies of interest are distant and faint. The building up of dark halos is best observed from the rotation of spiral galaxies, and 21-cm radio techniques are most powerful here. At redshifts of interest, the 21-cm line is shifted from 1.4 GHz down to frequencies as low as 0.5 GHz and even lower. Very large radio telescopes capable of operating at such low frequencies are needed. The SKA is likely to have this kind of capability, at least over part of the interesting redshift range.

The inner structure of dark halos, and also the Tully-Fisher law, is best studied using optical emission lines like H-alpha, which are redshifted into the near infrared. Good spatial resolution is needed, which requires telescopes with two-dimensional spectrometers at an infrared adaptive-optics focus. The Australian-built NIFS spectrometer, which will soon be operating on Gemini North, provides this kind of facility, and we expect it to be very useful for galaxies out to redshifts greater than 1. For more distant galaxies, larger optical telescopes with comparable integral field unit spectrometers will be essential.

4.5 Formation and evolution of supermassive black holes

4.5.1 Scientific motivation

Observations now show that almost all local galaxies, including our own Milky Way, contain supermassive black holes with masses of a million to several billion times that of our Sun. In the local Universe, these black holes are largely quiescent and are only detected by their gravitational influence. It is thought that a process of gas accretion builds up these black holes. During the accretion phase massive quantities of radiation are emitted and we observe this as an Active Galactic Nucleus (AGN). Powerful AGN (often called quasars or quasi-stellar objects (QSOs) are rare locally, but were up to a hundred times more numerous in the early Universe. Fundamental advances in our understanding of supermassive black holes and the AGN phenomenon have occurred over the last few years due to a combination of observations at all wavelengths, from radio to X-ray. However a number of science questions remain. The most critical of these are:

- How are super-massive black holes formed?
- What causes the evolution of AGN? What triggers AGN activity, and why is this less efficient at low redshift, at least for the most massive black holes?
- What is the influence of AGN on their host galaxy, and how is the relation between black hole mass and host mass built up? What is the detailed physics of the accretion process?

Resolution of these issues requires a broad range of observational and theoretical resources.

4.5.2 Australia's Current Strengths

Australia has strengths in a wide range of areas associated with studies of supermassive black holes and AGN. The survey facilities provided by the 2dF instrument on the AAT have allowed major surveys of distant quasars to be carried out, addressing issues regarding quasar evolution, large-scale structure and cosmology. Complementary observations at radio wavelengths have allowed investigation of the evolution of the radio-loud AGN population (see also Section 5.5). Australia’s access to the twin 8m Gemini Telescopes has allowed detailed optical follow-up of AGN, and there is a significant theoretical community working in areas such as the physics of accretion onto black holes and jet processes.

4.5.3 Future Requirements

a) Facilities

Because they are inherently multi-wavelength sources, the study of supermassive black holes (SMBH) and AGN requires a wide variety of tools. The following are critical for making continued progress on the key science issues identified above:

- Large amounts of time on major spectroscopic survey facilities, such as 2dF and its replacement AAOmega. Also, in the longer term instruments such as WFMOS on Gemini/Subaru.
- Access to X-ray telescopes, including Chandra and XMM-Newton currently (which have open access), and future telescopes such as Constellation-X and XEUS.

- High spatial resolution (adaptive optics) optical/infrared imaging and spectroscopy to probe the host galaxies of AGN over a wide range in redshift. 8m telescopes can do this at low redshift, but an ELT is needed for spectroscopy of hosts at high redshift.
- ELT for dynamical SMBH mass measurements in galaxy bulges at higher redshift that currently possible.
- High sensitivity radio observations to detect the "radio-quiet" AGN population. To begin with this will be via ATCA broadband correlator (and possibly xNTD), but SKA will allow observations of unparalleled depth, and will be able to detected all SMBHs at $z<6$ of mass $>10^6$ solar masses and accreting at >10 % of their Eddington limit.
- Megamaser detection and characterization in sources at cosmological redshifts. This requires SKA sensitivity and also space-based radio interferometry to give sufficient spatial resolution.
- Access to other facilities at a broad range of wavelengths including ALMA, Herschel, JWST.
- Supercomputer resources to enable the detailed theoretical modeling of accretion processes.

b) People

Major survey projects take a significant amount of manpower to be carried out effectively. Based on past experience, next generation surveys with instruments such as AAOmega might be expected to be carried out with collaborations of ~30 people, where 2 might be working full time on survey implementation and at least half of the rest spending ~50% of their time on survey related science. Generally, any increase in resources with regard to facilities should be met with a suitable increase in available research time to allow effective use of the facilities.

5. Other significant and related areas

In this section we discuss a number of other areas where considerable progress is expected in the next decade. In many cases, there are links to the major questions discussed above.

5.1 Evolution of the intergalactic medium

5.1.1 Summary

A key scientific strength of Australian astronomy is the evolution of the intergalactic medium through cosmic time. This medium is regulated by galactic/quasar radiation fields and galactic winds (GW), the same physical processes that are thought to dominate feedback in galaxy formation and evolution. The escape of ionising radiation from galaxies has close links with galaxy-scale outflows as we discuss.

Although great strides have been made over the past 25 years in understanding the physics and impact of GWs (and escaping radiation) in the local and distant universe, much work remains to be done to quantify the role of radiation fields and winds on the formation and evolution of galaxy-sized structures and the intergalactic environment.

This work is fundamentally multi-wavelength in nature, such that we require access to as many cutting edge facilities as possible. The key observational and theoretical issues which need to be investigated in the coming decade are listed below; a more detailed discussion is given by Veilleux et al. (2005).

5.1.2 Observational Challenges

Unbiased census of local galactic winds

The current sample size of GWs (~20) is thought to be a subset of the total class of wind objects. Most of the objects observed to date are under-luminous or only moderately powerful, compared to the most energetic systems which probably expel a large fraction of their metal enriched gas into the IGM. For example, our Galaxy's wind would be undetectable beyond the Local Group (Bland-Hawthorn & Cohen 2003). While it will be difficult to detect blown-away relics, there is a clear need to search the local volume systematically for winds. A multi-wavelength approach is needed to cover all phases of wind evolution. At optical wavelengths, the advent of tuneable filters on 8m class telescopes will improve tenfold the sensitivity of optical wind surveys. These instruments will be ideal for searching for galaxies with starburst-driven winds through the contrast in gaseous excitation between wind and star-forming disk.

An integral field spectrometer equipped with adaptive optics would complement tuneable filters by providing densely sampled data on kinematics, filling factor, and excitation processes. Chandra and XMM-Newton will continue to gather high-quality data on the hot medium in GWs. New long-wavelength radio telescopes (e.g., GMRT, GBT, EVLA, and SKA) can better search for the relativistic component of GWs. Particularly important will be to determine the relative importance of GWs in dwarf and massive galaxies.

Wind fluid

This component drives starburst-driven winds, yet has been detected in very few objects. Metal abundances suggest enrichment by SNe II, but the measurements are highly uncertain. Both sensitivity and high spatial resolution are needed to isolate the hot wind fluid from X-ray stellar binaries and the rest of the X-ray emitting gas, but no suitable instrument is planned for the foreseeable future. Indirect methods that rely on the properties of gas in the energy injection zone to constrain the wind pressure may be necessary. Current measurements of the pressure profiles in wind galaxies are certainly contaminated by the foreground/background disk ISM. Measurements in the mid- or far-IR with SST and Herschel will reduce the effects of dust obscuration.

Entrained molecular gas and dust

Despite the important role of the molecular component in GWs, high-quality mm-wave data exist only for M82. This is due to the limited sensitivity and spatial resolution of current instruments, but this will change soon. New mm-wave arrays (e.g., CARMA, and especially ALMA) will map the molecular gas in a large sample of nearby galaxies with excellent resolution (< 1"). Sub-mm and mid-IR data from the ground (e.g., SMA, JCMT, CSO) and from space (e.g., SST and Herschel) will constrain the amount and location of dust in the winds.

Zone of influence and escape efficiency

The environmental impact of GWs depends on the size of their zone of influence and on the fraction of wind fluid and entrained ISM that can vent from their hosts. Very deep emission-line, X-ray, and radio data on large scale would help tremendously to constrain wind extent. Tunable filters on 8m class telescopes may be particularly useful here. Absorption-line studies of bright background galaxies (e.g., high-z quasars, LBGs) have proven to be a very powerful tool to constrain the zone of influence of GWs at large redshifts. The Cosmic Origins Spectrograph (COS) on HST could extend the sample to a larger set of wind galaxies. Deep 21-cm maps of GW hosts on scales of up to ~100 kpc would help to quantify the effects of halo drag. The escape efficiency of winds may also be constrained indirectly by measuring the stellar metallicities of galaxies suspected to have experienced GWs (e.g., largely gas-free dwarf spheroids in the Local Group) and then comparing these values with the predictions of leaky-box models.

Thermalization efficiency

Observational constraints on the thermalization efficiency (converting supernova ejection energy into heating of the surrounding gas) of GWs are rare because of an incomplete accounting of the various sources of thermal energy and KE in the wind. A multi-wavelength approach that considers all gas phases is needed.

Wind/ISM interface and magnetic fields

Constraints on microphysics at the interface between the wind and galaxy ISM are available in only a handful of galaxies. High-resolution (sub-parsec scale) imaging and spectra of the entrained disk material in a sizable sample of local objects are required. The large-scale morphology of the magnetic field lines has been mapped in a few winds, but the strength of the field on pc scale is unknown. This information is crucial in estimating the conductivity between the hot and cold fluids.

Galactic winds in the distant universe

Absorption-line studies of high-z galaxies and QSOs will remain a powerful tool to search for distant GWs and to constrain their environmental impact. Future large ground and space telescopes will extend such studies to the reionization epoch. These galaxies are very faint, but gravitational lensing by foreground clusters can make them detectable and even spatially resolved. Cross-correlation analyses of wind galaxy surveys with detailed maps of the CBR (e.g., from the Planck mission) may also help to constrain the extent of the hot medium in winds by means of the Sunyaev-Zeldovich (SZ) effect (e.g., Voit 1994; Scannapieco & Broadhurst 2001), although one will need to consider all other foreground sources that affect the CBR (Hernandez-Monteagudo & Rubino-Martin 2004; Myers et al. 2004; (Hernandez-Monteagudo, Genova-Santos, & Atrio-Barandela 2004 and references therein).

Positive feedback by winds

Star-forming radio jet/gas interactions have been found in a few nearby systems (e.g., Minkowski's Object: van Breugel et al. 1985; Cen A: Oosterloo & Morganti 2005) and are suspected to be responsible for the “alignment effect” between the radio and UV continua in distant radio galaxies (e.g., van Breugel et al. 2004 and references therein).

The same physics may also provide positive feedback in wind galaxies. Convincing evidence for superbubble-induced star formation has recently been found in the disk of our own Galaxy (Oey et al. 2005). Shocked H_2 gas and circumnuclear rings of HII regions in a few wind galaxies may represent wind-induced star formation at the contact discontinuity/ISM shock associated with lateral stagnation of the wind in the galaxy disk. This region is also a gas reservoir from which to fuel the starburst. We do not know how often such rings form. Excess free-free emission on the inner edge of the outflow near the disk in M82 has been interpreted as a wind-induced starburst (Matsushita et al. 2004). A galaxy companion within the zone of influence of a GW may also be searched for wind-induced starburst activity (e.g., Irwin et al. 1987). This effect may have triggered the starburst in NGC 3073, a companion to NGC 3079 (e.g., Filippenko & Sargent 1992).

5.1.3 Theoretical Challenges

The ultimate goal of numerical simulations of GWs is to predict the impact of wind-driven feedback processes in star-forming and active galaxies on the galactic and intergalactic environments. We list in this subsection some of the key ingredients that are missing in current simulations to reach this goal:

Modelling the energy source

Current simulations do a poor job of modelling the energy source itself, especially in AGN-driven winds where energy and momentum injection rates are virtually unknown. Deeper understanding of AGN jets and winds is needed before simulating the impact of AGN-driven outflows. The situation for starburst-driven winds is much better, but the input energetics are still highly uncertain because the thermalization efficiency is constrained poorly by observation and theory. Simulations by Thornton et al. (1998) have shown that radiative losses of supernova remnants expanding into *uniform* media of ~0.02 - 10 cm^{-3} are ~0% - 90%. But it is important to run more realistic simulations with a range of molecular filling factors for young star clusters that evolve within a multiphase ISM.

Modelling the hot ISM

The work of Sutherland et al. (2003) is the first of a new generation of simulations able to handle a multiphase ISM with a broad range of densities and temperatures. Such sophistication is crucial to understanding and predicting the mass of gas entrained in winds. Simulations show that the initial encounter of clouds with a wind drives a strong shock that may devastate the clouds. Once in ram pressure equilibrium with the wind, however, clouds may accelerate to a significant fraction of the wind velocity before RT and KH instabilities shred them. To test the survival of entrained gas, these hydro processes should be combined with the effects of conductive evaporation to model the interface between the hot wind fluid and the dense ISM clouds. On the large scale, it will be important to use realistic distributions for the galaxy ISM, accounting for the clumpiness of the halo component and the disk, and possible large-scale magnetic fields. These simulations would quantify the drag of the halo gas, the impact of wind on disk ISM, and the feedback from wind-induced star formation.

Coupling the radiation field to gas

Current simulations do not account for possible coupling between the wind material and the radiation field emitted by the energy source or the wind itself, and indeed ignore radiation pressure. For instance, thick, dusty ISM clouds entrained in the wind may be photo-ionized by the hot wind fluid and radiative shocks at the wind/ISM interface, with major impact on their gaseous ionization.

5.2 The intracluster medium of galaxy clusters

5.2.1 Scientific motivation

Not all of the stars in clusters of galaxies lie within the galaxies themselves, and many stars are present in the space between the galaxies. In dense clusters like the Coma cluster, about half of the starlight comes from the intracluster stellar medium. In Coma and many other dense clusters, there are so many stars in the intracluster light that the diffuse cluster light can actually be imaged directly. In looser clusters like the Virgo cluster, the fraction of intracluster stars is only about 10%, and they are more difficult to detect.

The intracluster stellar medium is believed to come from stars that have been stripped from galaxies by the combined effect of fast encounters of galaxies and the tidal field of the cluster itself. The distribution of the intracluster stars, and the way that they move within the cluster, is therefore an invaluable tracer of the history of the cluster and the way in which it was built up.

How can we study the motions of the intracluster stars at the distances of the great clusters of galaxies? Like any other stellar population, the intracluster stars include some planetary nebulae (PNe), stars in the last stages of their lives which are throwing off an envelope of gas. This envelope becomes incandescent and for a brief period of about 10,000 years it reprocesses about 20% of the starlight into a single spectral line of oxygen. Searches for intracluster PNe emitting this line have been very successful, allowing us to identify these intracluster stars and also to measure their velocities. Most of what we know now about the properties of the intracluster stellar medium in clusters of galaxies comes from this kind of work.

The presence of a hot intracluster medium was first revealed by X-ray observations. The latest generation of orbiting telescopes is now able to probe small-scale structures in the X-ray emission associated with merger shocks or the lobes of powerful radio galaxies. Theoretical studies are now showing how dark matter plays a key role in cluster mergers.

The dynamic gaseous environment in which they are embedded shapes the properties of radio galaxies in clusters. Turbulence in the hot ICM is believed to exert a significant influence on radio source morphology and evolution. A particularly intriguing class of cluster radio sources are the large-scale radio halos and relics. These are extended, diffuse regions of radio emission (typically 1 Mpc in size and with no optical counterpart) which establish the presence of relativistic particles and magnetic fields in the ICM.

Their presence appears to be linked directly to merger activity and accompanying shock re-acceleration of particles (see Figure 2).

5.2.2 Future requirements

For the nearest galaxy clusters (Virgo and Fornax), at a distance of about 20 Mpc, efficient multi-object fibre spectrographs like AAOmega on the AAT are powerful enough to observe the intracluster PNe It will be possible to study thousands of PNe in these clusters and unravel their history. The nearest dense clusters, which are particularly important for this kind of work, are more distant. Coma, in which individual intracluster PNe have recently been detected, is at a distance of 90 Mpc. At such distances, larger telescopes (8m and larger) telescopes and novel techniques are needed. The instrumental requirements are for very efficient intermediate-resolution (R~3000-5000) spectrographs with as wide a field as possible.

The polarization properties of radio sources in or behind clusters are the main tools for probing cluster magnetic fields. Radio waves traversing the magnetized ICM show depolarization and rotation of the polarization position angle as a function of wavelength. Knowledge of the cluster magnetic field is crucial for understanding the global formation and dynamical history of clusters. The origin of cosmic magnetism is one of the key goals for SKA, and the ATCA is currently the only radio telescope in the southern hemisphere able to measure polarization accurately over wide fields of view.

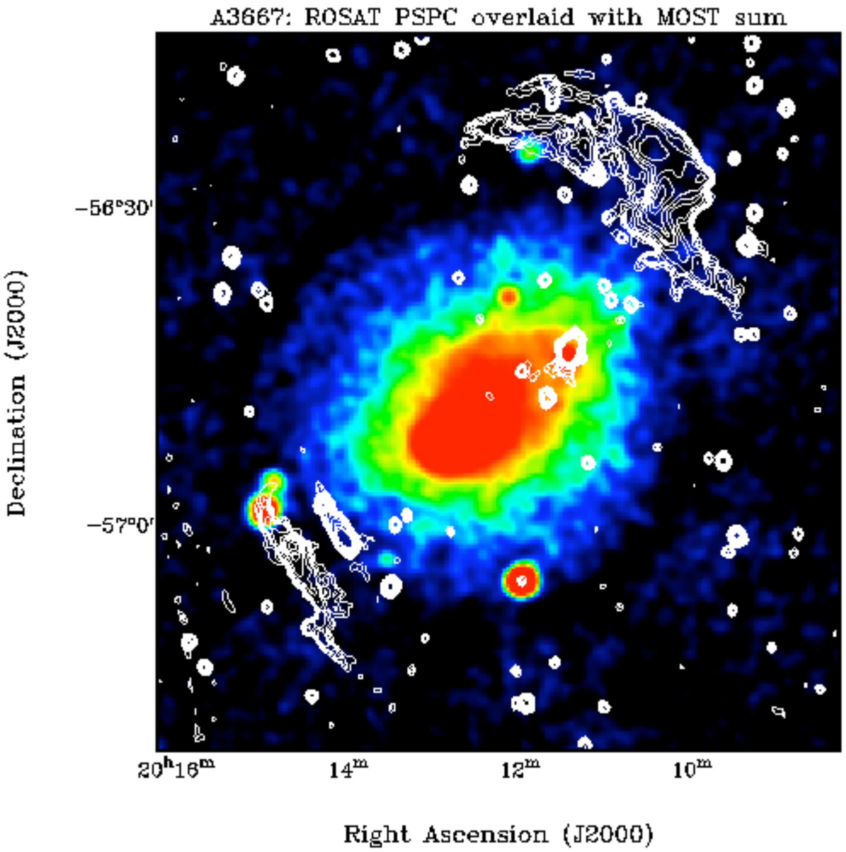

Figure 2. *A radio contour map from the Molonglo Observatory Synthesis Telescope at a frequency of 843 MHz, showing the spectacular giant radio relics in the galaxy cluster A3667. The contours are overlaid on a smoothed X-ray image from the ROSAT X-ray telescope showing the hot gas contained within the cluster.*

5.3 Nearby Galaxies and the Local Group

5.3.1 Scientific Motivation

For astronomers, the term "nearby" can comprise a large range of distances, generally depending on the astrophysical field of interest. This comes as no surprise as our knowledge of ever more distant structures in the Universe grows rapidly due to continuous advances in telescope size and instrumentation, theory and computing power. At the same time, our knowledge of local structures deepens and provides a reference point for the understanding of the evolution of the Universe.

For most cosmologists, e.g., galaxies closer than redshift $z = 1$ or 2 are generally considered nearby while for many Galactic astronomers a distance of 100 Mpc may appear rather far away. In this summary we consider galaxies in the Local Group (< 1 Mpc), the Local Volume (< 10 Mpc) and in the volume out to 100 Mpc. It is important to note that the signature of dark energy, which is generally inferred from measurements at cosmological distances, is also imprinted on the local Hubble flow as shown in recent N-body simulations by Macciò et al. (2005).

Another working group (WG2.2) is reporting on `The Nearby Universe' and decided to restrict its considerations to the Galaxy and the Local Group; we note any overlap where present.

The **Local Group** of galaxies is rather well defined, with our Galaxy and Andromeda the largest and most massive members of the group, accompanied by a very large number of dwarf galaxies. We currently know around 36 Local Group galaxies, several of which (e.g., Pegasus, Canis Major) were only discovered relatively recently. The galaxies belonging to the Local Group generally lie within one Mpc, although the borders of the group are not well defined. A few additional galaxies are known in the outer fringes of the Local Group but are believed not to be bound. The most prominent southern galaxies in the Local Group, apart from the Milky Way itself, are the Magellanic Clouds. Early surveys of neutral hydrogen revealed them to be interacting with each other as well as with the Milky Way. They present a most amazing nearby laboratory of astronomical processes. Several science questions related to the Magellanic Clouds are summarised in the report by WG2.2. As part of the Australian-led HI Parkes All-Sky Survey (HIPASS) we now have the first overall view of the neutral hydrogen gas (HI) associated with the Magellanic Clouds and the Milky Way. Using HIPASS, astronomers discovered new tidal features, e.g. the Magellanic Leading Arm, and mapped in detail the Magellanic Bridge and Stream.

The `**Local Volume**' (the sphere of radius 10 Mpc centred on the Local Group) includes at least 500 galaxies, many of which congregate in well-known groups like the Local Group, the relatively loose Sculptor Group and the more compact Centaurus A group. The first catalogue of galaxies within 10 Mpc was compiled about 25 years ago and contained 179 galaxies. The current count is 451 galaxies and the number is still growing. About 85% of the LV population are dwarf galaxies which contribute about 4% to the local optical luminosity density and roughly 10-15% to the local HI mass density. Because we can obtain independent distances to most galaxies in the Local Volume, we can deduce its three-dimensional structure and investigate the local Hubble flow. As stated above, the dispersion of the Hubble flow depends on the local energy/mass distribution and is thus a means of exploring cosmological parameters that are usually only accessible at larger distances. A `Local Volume HI Survey' (LVHIS) is now underway to study the HI content of LV galaxies complemented by deep infrared imaging, Hα imaging and 20-cm radio continuum observations.

The **volume out to 100 Mpc** has been covered with HIPASS which detected about 5000 galaxies, but only the most HI-massive galaxies (10^{10} Msun) are detected at a distance of 100 Mpc. About 10% of the galaxies detected in HIPASS had no previous optical identifications either because of their highly obscured location (e.g. behind the Galactic Plane), their low-surface brightness or their compactness which makes some galaxies difficult to distinguish from foreground stars. Large-scale structures seen in HI surveys appear much more homogeneous than those in optical surveys due to significant differences in the gas content and luminosity of galaxies in different environments. To obtain deep HI surveys much higher sensitivity is needed than available through current radio telescopes. The proposed xNTD can duplicate HIPASS in one week with the added advantage of high angular resolution (1 arcmin), high velocity resolution and large bandwidth.

5.3.2 Australia's strengths

Australia has excellent optical, radio and supercomputing facilities and respective astronomical communities to study the southern galaxies in the Local Volume (and beyond) with high sensitivity and resolution. A detailed multi-wavelength study of a complete sample of nearby HI-rich galaxies has just commenced and is expected to provide new measurements of the Hubble flow, Tully-Fisher relation, dark matter content of the individual galaxies (through rotation curves) as well as their star formation rates. While HST is needed in most cases to provide independent distances (using the tip of the red giant branch, Cepheid variables and surface brightness fluctuations) for the LV galaxies, the existing telescopes are capable to obtain the necessary optical, infrared and optical observations. Large amounts of dedicated telescope time as well as excellent students and postdocs are needed to accomplish this project.

5.3.3 Future requirements

Future requirements are a high-sensitivity radio interferometer like xNTD or SKAMP, and ultimately SKA to obtain deep HI surveys of nearby galaxies as well as explore the HI content of galaxies at large distances. The one arc minute angular resolution of xNTD would be a big improvement on HIPASS; nevertheless higher resolution will be need for follow-up HI studies. Especially important for the census of nearby galaxies is the study of low-mass galaxies and the low column-density outskirts and surroundings of galaxies. As the sensitivity of radio and optical observations increases we discover stars and gas at increasingly lower surface brightness and column density, respectively, which led to the discovery of faint stellar streams and intra-group gas. High sensitivity two-dimensional spectrometers are needed to study the kinematics of the ionised gas in galaxies through Hα velocity fields.

5.4 Evolution of Galaxy Clusters

5.4.1 Scientific motivation

Clusters of galaxies are the most massive gravitationally bound objects in the universe. As such they provide a remarkably useful tool for probing cosmology.

Clusters typically contain thousands of galaxies surrounded by a hot, X-ray emitting plasma, both of which are contained within a massive halo of dark matter. The X-ray emission from the plasma provides an accurate way of measuring the total mass of the cluster, the mass of the plasma, and the density of the plasma. Thus clusters provide an extremely well defined ‘laboratory’ in which to study the evolution of galaxies; interactions between galaxies, interactions with the intergalactic medium, and the distribution, and consequently the nature of dark matter can all be studied in the laboratory of clusters.

According to current theories, structure in the universe assembles hierarchically, with smaller structures merging to form larger structures. Thus, clusters, as the most massive bound objects in the universe, will be the most recent objects to have formed, and so the build-up of structure will be easier to detect in clusters, since evolution in their properties is likely to occur over shorter look-back times. The exact epoch and nature of this hierarchical assembly will depend upon the underlying cosmology of the universe. Thus clusters are sensitive tools with which to measure the key cosmological properties of the universe.

There are a number of key questions that still need to be addressed in cluster studies:

Galaxy evolution:

When do cluster galaxies assemble? When does star-formation occur in cluster galaxies? What are the mechanisms responsible for cluster galaxy formation and evolution? Do they form via mergers? When do any such mergers take place and how do they affect the galaxies?

How does environment affect galaxy evolution? How do the properties of galaxies in the infall regions of clusters compare to galaxies in cluster cores? Are galaxies transformed via interactions with the intergalactic medium? How do feedback processes affect the intergalactic medium?

Structure formation:
When do clusters of galaxies assemble? How does this depend on the mass of a cluster? How is the mass of a cluster distributed at different epochs? Does cluster assembly take place along filaments as in numerical simulations? How does the formation of clusters relate to the properties of dark matter and dark energy?

5.4.2 Australia's Role & Necessary Facilities

Australia's role in studying cluster evolution has traditionally been focussed on optical and near-infrared observations of galaxy evolution. The background and expertise in this area can be built upon by applying techniques previously only possible on nearby galaxies, of which we now have a good understanding, to systems at redshifts > 1, when the universe was less than half its present age. The faint nature of high redshift sources necessarily dictates the use of large-aperture telescopes, such as the existing 8m Gemini telescopes, and future ELTs.

Necessary instrumentation includes wide FOV near-infrared imaging, to map the distribution of galaxies in clusters, and measure their rest-frame optical and NIR luminosities, high multiplex-gain multi-object optical and NIR spectrographs, with low resolution, to determine cluster membership, and higher resolution to measure emission and absorption lines and hence quantify star-formation activity.

High spatial and spectral resolution X-ray observations, with the XMM and Chandra telescopes, will continue to be very important as a means of probing the dynamical state of clusters, their build-up through major and minor sub-cluster mergers, and studying in detail the physics of the hot ICM.

Additionally Australia's strong background in radio astronomy can be used with 12mm radio observations using the AT the Compact Array, which will allow detections of the Sunyaev-Zeldovich (SZ) effect at resolutions of tens of arcminutes to map out the distribution of the intracluster gas, measure the mass, and observe the assembly of clusters. Future (and already-funded) upgrades to the Compact Array bandwidth will hugely extend the sensitivity of these observations, and a planned future 7mm receiver will allow more precise SZ measurements on even smaller, sub-arcminute scales.

5.5 Evolution of radio galaxies

5.5.1 Scientific Motivation

The past decade has seen a convergence of three fields of astrophysical research that have been highlights of Australian astronomy to date - Active Galaxies, Cosmology and Galaxy Formation. There are two main reasons for this: (1) High-redshift radio galaxies and quasars are beacons of the densest regions in the Universe, at epochs when galaxies were starting to form; and (2) There appears to be a symbiotic feedback process at work, between forming galaxies and their central black holes, which is manifest in a correlation between the masses of the black hole and the bulge of the host galaxy (the Magorrian relation, Magorrian et al. 1998) and also in the accumulating evidence for jet–induced star formation at early epochs of the Universe.

Australian astronomers, both theoreticians and observers, are pursuing many aspects of the relationship between active galaxies, cosmology and galaxy formation, and this work will develop significantly into the next decade. Research will not only involve the high-redshift Universe, but also objects located closer to us. Elucidation of the physical processes occurring in the nearby Universe informs our investigations at high redshift. This is an example of near–field cosmology pursued in other areas.

Some of the important related investigations to be developed or undertaken include:

- How do quasars form at various epochs of the Universe and what makes some of these objects become intense emitters of radio waves? This involves, in part, a fundamental understanding of the processes of accretion in the environments of black holes and how, in particular, these lead in some cases to the production of jets moving at speeds close to the speed of light.
- A fundamental question in this field is how super-massive black holes form less than a billion years after the Big Bang, and how jet-induced star formation might produce a significant fraction of the first generation of stars. This topic requires an intense observational program on large optical telescopes, both ground–based and space–based. Observers will use high quality spectra of radio galaxies at redshifts of 6 or greater, to understand the processes of jet-ISM interactions and chemical enrichment at early epochs. Supercomputer simulations off jet-ISM interactions, in the context of an evolving cosmology will enable us to understand the relevant physical processes and to inform the observational program.
- Another fundamental theoretical and observational question relates to the combined roles of dust, star formation, active galactic nuclei and chemical evolution in the early Universe, and how these affect the spectral distribution of the observed radiation from radio through to X-rays.
- Black holes produce both intense radiation and energetic outflows from their surrounding accretion disks, both of which impact on the surrounding medium. As well as the star-formation processes alluded to above, these interactions may well be responsible for establishing the relationship between central black hole masses and the final bulge mass of the host galaxy. However, the physical details are not understood. Current work on the interactions of jets and outflows from black holes with the interstellar medium, and the interaction between forming galaxies and black holes, will continue to develop as supercomputers become more powerful and sophisticated new codes are developed.
- Associated with the details of black hole-galaxy formation symbiosis is the question of the baryon mass fraction in current epoch. The baryon mass fraction implied by the standard model of big bang nucleosynthesis (BBN) is approximately 0.15. The galaxy baryon mass fraction is less than the BBN value (typically less than 0.1 and in some cases much less). However, starburst – driven outflows (for low mass galaxies) and black hole – driven outflows (for high mass

galaxies) may be responsible for enriching the intergalactic medium. This will be an active topic of observational and theoretical research over the next decade.

5.6 Gravity waves and cosmology

5.6.1 Scientific motivation

Gravitational waves from in-spiralling massive binaries contain, as a direct observable, the source's luminosity distance, but not its redshift; they also contain the masses and spins of the in-spiraling bodies. Several cosmological applications are based on this:

- Measurement of the distribution of black hole binaries with luminosity distance. Ground based detectors coming on line around 2010, such as Advanced LIGO (A/LIGO) will measure binaries with masses below about 1000 M_{sun} out to a redshift of about 2. The Laser Interferometer Space Antenna (LISA), possibly operational by 2014, will measure binaries with masses between about 10^5 and 10^7 M_{sun} out to redshifts of 30 or so. Such observations will give information about the formation of structure in the early universe.
- If the galaxy clusters in which a few of these merging binaries lie can be identified, then the combination of electromagnetic redshifts and gravitational distances can be used to map out the distance-redshift relation and thereby obtain information about the dark-energy parameter.

Gravitational waves are the only form of radiation that arrives from the first second of the universe, unscathed by absorption or scattering. A/LIGO, LISA and radio telescopes such as the SKA will search, in complementary frequency bands, for waves from the first second. Possible sources are:

- Phase transitions in the first second, e.g. associated with the separation of the electroweak force into the electromagnetic and weak forces, for which the gravitational waves would be in the LISA band.
- Bursts from cosmic-string cusps and kinks. String theorists argue that some fundamental strings may have been inflated to cosmic size during early inflation, and the resulting cosmic-string gravity waves may be detectable by LIGO (even, possibly, initial LIGO) or by LISA.
- Waves created by inflation in the first 10^{-24} seconds, which carry information about the energy parameter (expansion parameter) of inflation. For conventional inflation, these are best seen via their imprint on the polarization of the CMB.
- Waves produced in the Planck era in pre-big-bang string-cosmology scenarios. It is predicted that such waves might be in the LIGO or LISA band.

In addition, gravity wave backgrounds comprised of astrophysical sources throughout the universe will provide new probes to the high-z universe. Using the technique of cross correlation it is possible to detect the combined effects of very large numbers of background signals that would otherwise be below the threshold of a single detector. This approach is especially relevant to the detection of the background of signals from supernovae, neutron star births and neutron star coalescence events throughout the universe. The technique offers the possibility of probing star formation to red shifts ~3-5.

5.6.2 Australia's existing strengths

Australia's strengths in gravity wave detection are reported elsewhere in this document. Through the Australian Consortium for Interferometric Gravitational wave Astronomy (ACIGA) we are playing a major role in the development of the physics and technology of next generation (A/LIGO, LISA) detectors and are important contributors to the development of the data analysis pipeline for LIGO. ACIGA has over 50 members and has a number of major facilities including: the high optical power test facility at Gingin in Western Australia; the advanced interferometry laboratory on the ANU campus; the University of Adelaide's high power laser laboratory; and ACIGA Data Analysis Cluster at the ANU. The Gingin facility is being used to develop infrastructure for a future long baseline gravity wave detector.

5.6.3 Future requirements

To secure Australia's role in the first detection of gravity waves, access to high quality gravity wave data and our participation in astrophysical searches (CW, stochastic waves, bursts and in-spirals etc) requires our partnership in a major international facility. We have been offered full partnership in A/LIGO, the first upgrade to the US LIGO detectors. This upgrade has been costed at US$150M. The Australian subscription would be US$5M. Exploitation of the science would require a team on the order of 10. Delivering lucrative sub contracts (guaranteed to be worth no less than the subscription fee) obtained via the partnership would involve on the order of 30 scientists and engineers, depending on the number of contracts.

Location of gravity waves sources to within at least a galaxy cluster will be crucial to extracting the maximum science. For best angular resolution a global array must contain a full-size detector in the southern hemisphere, with initial studies showing that a site in Western Australia is optimum. Furthermore, an Australian site provides the global array with optimum sky coverage at maximum sensitivity. With the regular detection of gravity waves, the case for an Australian detector funded by an international consortium will be secured. With A/LIGO coming on line around 2010, it is very likely that this case will be made within the period covered by this decadal plan. The Australian team put together to deliver A/LIGO will need to be augmented, to build and operate a major gravity wave telescope. In the first instance an advanced technology, intermediate length but extendable, interferometer may be funded by Australia from its contribution and in kind international support. Such an instrument would be capable of extracting gravity wave science, when operated in coincidence with northern hemisphere detectors, over a limited frequency range.

Detecting stochastic sources using ground based detectors needs at least a pair of reasonably close (< ~ 1000 km) antennae. These searches will be carried out by the A/LIGO array and possibly by a pair of European detectors (the French Italian VIRGO detector and a new European detector).

Whilst ACIGA is carrying out crucial R&D for LISA, the route to direct Australian participation in a NASA/ESA space mission is unclear.

6. Required resources

Here we summarise the resources required by the science areas discussed above. For each of our three key science areas we list the key instruments that will enable the science, along with a second tier of facilities that will further enhance Australia's capabilities.

6.1 Dark energy and the equation of state of the Universe

Further understanding of the nature of dark energy will come about via a number of avenues. These different approaches will be largely complementary, providing orthogonal constraints on various models. Large-scale spectroscopic surveys are a powerful approach. These require massively multiplexed, high-efficiency systems on large telescopes. AAOmega, to come into operation at the AAT in 2006 will be the most effective instrument for this kind of survey for a number of years. This will enable major redshift surveys of hundreds of thousands of galaxies at redshifts $z<1$, and is fully accessible to the Australian community. WFMOS (on the Gemini or Subaru 8m telescopes) will provide an order of magnitude improvement in wide-field spectroscopic capabilities (likely to come into operation ~2012). This facility is not currently funded, but construction is likely to be by a multi-national team lead by the Anglo-Australian Observatory. This will enable measurement of the equation of state of the Universe up to a redshift of ~3 via large-scale redshift surveys. The SKA pathfinder will also be able to carry out redshift surveys to $z\sim1$ by detecting HI emission, and is also likely to come into operation ~2012. The SKA itself will provide close to an order of magnitude improvement by detecting $\sim10^9$ galaxies at $z<1.5$ and $\sim10^{6-7}$ at $z\sim3$ (Rawlings et al. 2005).

The current high-redshift supernovae programs will continue to require a significant amount of effort. In particular, follow-up on broad range of ground based telescopes (4m and 8m). The next large leap in this area will be with the Joint Dark Energy Mission (JDEM), if it is funded. This is a US program with low to moderate Australian involvement.

Other resources, which could contribute to this field, include the ANU SkyMapper telescope, which should discover many new supernovae, and a telescope in Antarctica (i.e. Dome-C), which could use the high quality imaging performance at Dome-C to undertake a large area weak gravitational lensing study. Also, a new survey of radio sources with xNTD would enable measurement of the integrated Sachs-Wolfe effect.

Primary Facilities	Date	Science
AAOmega	2006	Z<1 redshift surveys for w(z)
WFMOS	2012	Z=1-3 redshift surveys for w(z)
SKA Pathfinder	2012	Z<1 redshift surveys in HI for w(z)
JDEM	2015	W(z) from supernovae & lensing
SKA	2020	Z=1-3 redshift surveys in HI for w(z)
Secondary Facilities		
SkyMapper	2007	Detection of new supernovae
Antarctic 2m	2009	W(z) from lensing
xNTD	2008	Integrated Sachs-Wolfe effect

6.2 The first luminous objects and the epoch of reionization

The facilities crucial to investigate this epoch fall into two classes: those aimed at the detection of the first sources, and those focusing on the detection of neutral hydrogen emission. For the follow-up of the first sources, detection of supernovae and GRBs will be crucial. Satellites such as SWIFT (2004) and GLAST (2006) will provide large numbers of GRBs and given the significant amount of follow-up required, GRB data is likely to be open to the whole astronomical community. Follow-up of the most distant GRBs and supernovae from population III stars is likely to require an ELT. JWST will also be able to make direct detections of the first star clusters at z>10.

To detect the signature of neutral hydrogen at high redshift requires a large area low frequency facility (~80-300 MHz). The Low Frequency Demonstrator (LFD) is one such facility which will attempt this work (the Dutch LOFAR project is another) and is a joint Australian/US project, although in the long term a facility much larger than the currently funded LFD is required to make detailed measurements (order of 10 times larger).

Primary Facilities	Date	Science
SWIFT	2004	GRB detections
GLAST	2007	GRB detections
ELT	2015-2017	Discovery of population III SN and follow up of GRBs
JWST	2012	Detection of the first star clusters at z>10
LFD	2008	Detection of the neutral hydrogen signature
LOFAR	2010	Detection of the neutral hydrogen signature
SKA	2020	Detection of the neutral hydrogen signature, high redshift CO surveys
Secondary Facilities		
SkyMapper	2007	Discovery of new high redshift quasars.

6.3 Understanding the formation and evolution of galaxies

Understanding the complex and detailed physics that goes into the formation and evolution of galaxies will require a broad and substantial set of resources. In the short to medium term, access to 8m-class telescopes is a priority. In particular both imaging and spectroscopy are crucial in two modes, wide-field and high special resolution (adaptive optics assisted). The small share of 8m time currently available through Gemini appears to be a significant barrier to major programs. In particular, wide-field high-resolution optical/infrared imaging/spectroscopic facilities are required, such as those potentially available on the Japanese Subaru Telescope. In the short-term, access to Subaru or increased access to Gemini are encouraged. However neither, facility naturally leads into an ELT program. Although ESO still represents the clear front-runner ensuring access to more 8m time, as well as a path to an ELT and sub-mm facilities (via ALMA), the Magellan group probably represents a more realistic option. When ELTs come on line, they will provide a range of new abilities, including studies of resolved stellar populations in nearby galaxies and detailed kinematical studies to z ~3. Although ELTs may only start to come on line in ~2015, it is vital that Australia is involved in an ELT project.

The wide field of view of AAOmega on the AAT make this facility a key tool in the next decade for study of large samples of galaxies. This will only be superseded by WFMOS, which will allow an order of magnitude more objects to be targeted. JWST's ability to view high redshift sources at high resolution will be unprecedented in the infrared. Currently, Australian access to JWST is unclear.

ALMA will be critical in detecting gas (e.g. CO) and finding dusty sources at high redshift. Currently it is unlikely that Australia will have direct access to ALMA. In this case, it is important that the community finds a way to leverage time via other facilities. One possibility would be via ATCA time using the 15-50 GHz region and the wide band correlator (ALMA will only work above 100 GHz).

The SKA, although it will not be operational until ~2020, will provide a unique facility which Australian astronomers must have access to. SKA (and SKA pathfinder) will have a significant role to play in studying the HI content of galaxies to high redshift.

In order to understand the co-evolution of SMBHs and their host galaxies, further observations at X-ray wavelengths will be required. Australian astronomers currently have access to the Chandra and XMM-Newton X-ray satellites, but there are only a limited number of Australian researchers with experience at X-ray wavelengths. Next generation X-ray satellites will cause significant further progress in this area (Constellation-X and XEUS). It is expected that these will be open access as for previous X-ray satellites, but effective exploitation requires a significant X-ray community to be built up. Australia could benefit from a centralised Space Telescope Unit to liaise with ESA, STScI, support applications, and assist with access, analysis and awareness of ongoing and upcoming missions.

Other facilities which will have a role to play in this area, are the ATCA with high redshift CO detections and increased sensitivity from the new broadband correlator, SKAMP (for HI and continuum studies), xNTD (HI), an Antarctic telescope and gravity wave detectors.

Primary Facilities	Date	Science
Optical/IR 8m	Present	Wide-field imaging and spectroscopy, high spatial resolution (AO) imaging and spectroscopy (inc. IFUs),
Chandra/XMM-Newton	Present	AGN surveys and investigation of SMBHs
AAOmega	2006	Galaxy redshift and stellar population surveys, AGN surveys
WFMOS	2012	Galaxy redshift and stellar population surveys, AGN surveys
JWST	2012	High redshift galaxies
ALMA	2010	Gas at high z via molecular lines, dusty (star-forming) objects at high redshift.
ELT	2015-2017	High redshift galaxies, resolved stellar population in nearby galaxies
SKA pathfinder	2012	HI surveys to z~1
SKA	2020	HI surveys to z>3, star forming galaxies to z~5, detection of "all" accretion SMBHs at z<6, HI rotation curves at high z
XEUS/Constellation-X	2014	SMBH accretion physics (inc. Fe line emission), hot gas in galaxies.
Supercomputers		Theoretical modelling and simulations
Secondary facilities		
Spitzer	Present	SMBHs, star formation
ATCA	Present	CO observations at 15-50GHz
SKAMP	2007	HI surveys to z=0.3-0.4
XNTD	2008	HI surveys to z=0.2
Antarctic 2m	2009	Z~1 galaxy properties
LISA	2014	Gravity waves
Space liaison unit		

6.4 Other facilities

There are also a broad range of facilities that are required for the other science areas discussed in section 5.

Primary Facilities	Date	Science
Optical/IR 8m	Present	Kinematics of the IGM (IFU, AO, tuneable filters). Intracluster PN (R~3000-5000 wide-field spec.), galaxy clusters (wide field of view IR imaging and optical/IR spectroscopy)
Chandra/XMM-Newton	Present	Hot IGM, galaxy clusters
GMRT, GBT, EVLA	Present	Relativistic IGM
Spitzer/Herschel		Dust in the IGM
AAOmega	2006	Intracluster PN
ALMA	2010	Dust in the IGM
SKA	2020	Magnetic fields in the ICM, deep HI of nearby galaxies
XEUS/Constellation-X	2014	Galaxy clusters
Supercomputers		Jet accretion disk simulations
ATCA	Present	Magnetic fields in the ICM, SZ effect in galaxy clusters
XNTD	2008	Deep HI of nearby galaxies
LISA	2014	Gravity waves (~10^{5-7} solar mass binaries)
A/LIGO	2010	Gravity waves (<10^{3} solar mass binaries)

6.5 Facilities beyond the next decade

While the main goal of the decadal review is to address the issues regarding astronomy research in the next 10 years, the long-term nature of the next generation of facilities means that there is considerably more than 10 years from first concept to a fully functional instrument. Thus it is critical that in the next decade Australia positions itself to play a key role in the next generation facilities that will come on line after 2015. We therefore highlight the critical role that the SKA and ELTs will play in astronomy after 2015; a wide range of science areas discussed in this report will be revolutionized by these facilities. A third major advance in the next decade is likely to be in the first detection of gravitational waves, opening a new window for cosmological studies, particularly with the operation of LISA in ~2014.

6.6 Facilities vs. people

One of the most regularly discussed issues at WG meetings (and particularly town hall meetings) was the limited amount of time that many researchers have. In particular, it was recognized that to make effective use of any expansion of facilities, extra research effort is also needed. Therefore funds need to be set aside for postdoctoral positions as part of the funding of major facilities. The community could also take advantage of some re-structuring to reduce the number of committees, working groups etc.

7. Contributors

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