WG 1.3 - The Galaxy

Chairs: Naomi McClure-Griffiths & Jill Rathborne

V1.5 – 28 August 2014

Executive Summary

The next decade will provide a detailed picture of the Galactic interstellar medium, the formation of stars within it, and an ability to extrapolate this knowledge to understand galaxy evolution across cosmic time. This cutting-edge science will be made possible through wide-field, multi-object optical spectroscopy and high-resolution follow-up on 6 – 10m class telescopes, exploitation of the unique capabilities of the world-leading millimetre telescope ALMA, and all-sky centimetre and metre-wave surveys with ASKAP, the MWA, and SKA phase 1.

Introduction

This Working Group is tasked with assessing the scientific goals pertaining to studies of the Milky Way galaxy for 2016-2025. Our objective is to identify the key science questions that Australian astronomers will have a major role in answering over the next decade and the resources, facilities and collaborations needed to enable our participation and leadership in this scientific arena.

As a Working Group we are tasked with presenting a report to the National Committee for Astronomy, which will provide input to the writing of the Decadal Plan. Our report is based on information collected from the Working Group membership and the community at large.

Extrapolating our knowledge to understand galaxy evolution

Understanding the evolution of galaxies remains a major challenge and one that will drive much research for the next decade. Galaxy evolution is intimately linked to the conversion of warm, diffuse interstellar gas into cold molecular gas and ultimately into stars. The Milky Way and Magellanic Clouds each provide unique windows into the evolution of galaxies. Studying star formation, gas evolution and galaxy interaction in these nearby systems reveals these processes in a level of detail that resolves the important physical processes in different galactic environments and with different metallicities. Indeed, the central few hundred parsecs of the Milky Way, the Central Molecular Zone (CMZ), represents an environment quite different to the rest of the Galaxy and the Magellanic Clouds, but which is in many respects comparable to that in star-forming galaxies at high redshift ($z>2$). By extrapolating our knowledge of the detailed physics derived locally to the most extreme conditions in the Universe, we can better understand the processes that influence galaxy formation and evolution, including the formation of stars and clusters.

In the coming decades, ALMA and the SKA will resolve individual stellar nurseries in other galaxies with comparable sensitivity and angular resolution to observations conducted within our own Galaxy in the past decade. As such, we are poised to not only understand the detailed interactions within the ISM and star formation within the Milky Way, but also for the first time, be able to expand this knowledge to understand star formation and galaxy evolution across cosmic time.

Over the next decade we expect Australian astronomers to contribute significantly to answering some of the big questions that drive modern astrophysics, including:

- How did the first stars form?
- What galactic conditions affect star formation?
- How do galaxies interact with their surroundings?
- What is the structure of the Galaxy?

Progress against objectives in the 2006-2015 Decadal Plan

The *Nearby Universe* Working Group of the 2006-2015 Decadal Plan listed a number of science questions related to the Galaxy and Magellanic Clouds. We highlight several of these below and summarize progress made over the last decade toward answering them.

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

This area includes one of the biggest success stories from the 2006-2015 decadal plan. Australian astronomers are leading the discovery rate of extremely metal poor stars using both Australian and International facilities. Last decade's report identified the need for wide-field, optical photometric surveys using 1-2m class telescopes, a goal that has been realized. In the past year, the SkyMapper facility (despite technical difficulties and delays in operations) has discovered the most metal-poor star known in the Galaxy (published in Nature in 2014). Key to the understanding of this star was follow-up observations with Magellan, which confirmed the detection and provided constraints on the star's formation history. Unfortunately, a major shortcoming in the last decade has been the failure to deliver on the goal of significant and on-going 8m-class telescope national access. If carried into the future this will hinder Australia's leadership position in the discovery and interpretation of extremely metal-poor stars.

Last decade's report also identified the power of studying star formation in the Magellanic Clouds as an analogue of the chemically poor and UV radiation dominated environment in which the first stars formed. Specifically, the report suggested that studying the mass function of molecular clouds within the Magellanic Clouds would provide useful constraints on theories of star formation. The report outlined options such as focal plane arrays on Mopra and access to ALMA to provide the necessary capabilities, however, tremendous progress was made instead with large-scale single-pixel feed mapping of the LMC through Mopra's MAGMA survey. The MAGMA project has measured the mass function of GMCs in the LMC and provided excellent finding charts for ALMA observations. Also, the Methanol Multibeam (MMB) Survey made the first complete, sensitive search for interstellar masers in the Magellanic system and found a significant deficit in this high-mass star formation tracer.

What is the life story of the Milky Way galaxy?

The past decade has seen significant leadership from Australian astronomers in uncovering the life story of the Milky Way, through the study of `Galactic Archaeology' that focused on the formation and evolution of our Galaxy using stellar abundances and kinematics. Much of the research related to Galactic Archaeology originated in Australia and our astronomers are world-leading experts: the RAVE survey with a core Australian team was the very first Galactic Archeological survey. The impact internationally is best demonstrated by the commencement of large international surveys including Gaia-ESO and APOGEE, which are primarily aimed determining stellar abundance and kinematics. The last decadal plan highlighted the need for high-resolution spectroscopy on 1 – 8 m telescopes. This requirement has been realized with the unique HERMES spectrograph on the AAT, which combines high resolution, high multiplex, and a wide field of view. HERMES is currently being fully commissioned and a million-star world-first survey will commence shortly.

Our understanding of the stellar composition of the Galactic halo has progressed significantly over the past decade. Australian astronomers led studies that found 4 out of the 5 most metal-poor stars, and have been involved in studies to disentangle the nature of the halo, particularly addressing whether it is a dual halo with different stellar populations and kinematics. The duality of the Galactic halo in particular provided a new picture for the formation of the Milky Way within the context of the hierarchical model of galaxy assembly (published in Nature in 2007).

Tidally disrupted dwarf galaxies are potential building blocks of our Galaxy although evidence of this is scarce. Australian astronomers have been at the forefront of this research, looking for such evidence. Furthermore spectroscopic and HST-based photometric observations have indicated that most globular clusters contain multiple populations whose origin, and relation to the observed abundance variations, is not well understood. Australian astronomers have made many key discoveries into the nature and origin of globular clusters.

The chemical evolution of the Universe is governed by the chemical yields from stars, which is in turn determined primarily by the initial stellar mass. Prior to 2003, there were no stellar yields from detailed stellar models of low and intermediate-mass stars, which account for the majority of the stars recycling gas and dust in our Galaxy. This led to crucial gaps in our understanding of the chemical evolution of key elements such as carbon, nitrogen, fluorine, and heavy elements produced by the slow neutron capture process. Over the past decade, Australian astronomers have made considerable progress in this area by providing the international community with theoretical stellar yields covering a larger range in mass and composition than previously available.

Although not identified as a goal in the last decadal plan, significant inroads to understanding the life-story of the Milky Way have been made in the area of gas evolution of the Galaxy. Australian astronomers have led and are leading surveys with Parkes, Mopra and the Australia Telescope Compact Array to provide insight into the evolution of gas within the Milky Way and its halo. Moreover, these surveys have also provided new insights into the interaction of the Magellanic Clouds with the Milky Way, the nature of the high velocity clouds that contribute to the gas-feeding of the Milky Way, and the evolution of gas from atomic to molecular.

Understanding the life story of the Milky Way must also include an understanding of the processes by which the most massive stars are formed. In the past decade Australian astronomers have played critical leading roles in many large surveys that aimed to characterize the dense gas environments where high-mass star formation occurs and to search for associated star formation activity via maser emission. Surveys of interstellar masers and thermal molecular lines, such as HOPS, MALT45, MALT90, MMB, and the CO mapping of the disk/CMZ conducted with Mopra, Parkes, and the ATCA provide a wealth of information about the environments of high-mass star formation across the Galaxy and will have long-lasting legacy value as observations with the new large, international telescopes such as ALMA and the SKA begin. These surveys provide critical complementary information to space- and ground-based continuum Galactic Plane surveys conducted in the past decade (*Spitzer*, *Herschel*, Bolocam, ATLASGAL) and have allowed Australian astronomers to make significant advances in characterizing the global properties within these environments and developing an evolutionary scheme. The success of the Australian-led molecular line surveys have given Australian astronomers a unique position to be highly competitive in gaining access to ALMA in its early science phase. Indeed, follow-up projects that use these surveys as finding charts have been successful in gaining highly competitive ALMA time in all three Early Science cycles.

What is the origin and evolution of cosmic magnetism?

The last decadal plan identified a clear goal of measuring the structure and geometry of magnetic fields in the Milky Way and nearby galaxies to inform our understanding of the origin and evolution of magnetism. To this end, great strides have been taken over the past decade. Measurements of rotation measures of pulsars, together with rotation measures towards extragalactic sources from the Southern Galactic Plane Survey and other ATCA (plus VLA, DRAO and WSRT) data have added great insight into the large-scale structure of the Milky Way's magnetic field. These measurements have set limits on dynamo theory for our own Milky Way, as well as the Large and Small Magellanic Clouds. Measurements of diffuse polarized emission have revealed information about the turbulent nature of the magnetized, ionized medium of the Galaxy and led to the discovery of a magnetized component to the large wind bubble from the Galactic Centre. The technique of “Faraday synthesis" has advanced in the last decade and surveys with Parkes have delivered on the identified goals of revealing the magnetized fluctuations in interstellar gas.

The last Decadal Plan report identified a number of capability developments and surveys that have, to a large extent, been achieved. These are:

- The development of GHz bandwidth receivers on the ATCA with good polarization purity that provide high sensitivity, broad-bandwidth Faraday synthesis measurements for studying the Galaxy's magnetic field
- A survey of the diffuse polarized emission from the southern sky has been realized with the S-band Polarization All-Sky Survey (SPASS) at 2.4 GHz and also the Global Magneto-Ionic Medium (GMIMS) at 300 – 450 MHz & 1300 – 800 MHz. The extragalactic polarized sources from S-PASS, together with many other polarization databases observed with the ATCA, have complemented the NVSS in the north to cover the entire sky.
- The development of a sensitive wide-field low frequency interferometer in Western Australia. What was then identified as the Low Frequency Demonstrator, has become the Murchison Widefield Array, which has recently begun observations of the low-frequency polarized sky
- Deep polarization surveys at high sensitivity with the planned extended New Technology Demonstrator (xNTD) were also identified. Although these have not yet been realized, they are anticipated with ASKAP.

Scientific Drivers for 2016 – 2025

Galactic science is set to make major contributions to our knowledge of the Universe, using the Milky Way and Magellanic Clouds as the laboratories for detailed studies of how galaxies work. Our Working Group has identified five high-impact science questions that will be answered over the next decade. We discuss each of these below and summarize the required capabilities needed to answer them. We list the questions in order of the scale that they describe, beginning on the large scale and ending on the small scale.

How does the Galaxy interact with its circumgalactic environment? What are the physical properties, including magnetic configuration, of the halo?

Galaxies are not closed systems. The evolution of the Milky Way is significantly impacted by the two-way flow of gas and energy between the Galactic disk, halo, and circumgalactic environment. Cosmological simulations predict that gas accretion onto galaxies is on-going into the present epoch. Furthermore on-going accretion is essential to maintain the star formation rate as measured in galaxies across cosmic time. The Milky Way is no exception, given the current gaseous reservoir of the disk and the current star formation rate, it is clear that the Galaxy would exhaust its supply of fuel in only a few Gigayears. Naturally, a significant topic of research related to the evolution of the Milky Way involves understanding how the Galaxy acquires fresh fuel. Over the next decade we expect significant progress in this area through multiple avenues.

One potential source of fuel for disk galaxies is via gas accretion from the disruption of neighbouring dwarf galaxies. The Magellanic System, created from the interaction between the Small and Large Magellanic Clouds and the Milky Way, provides the closest example of galaxy fuelling. Using the combination of spatial coverage and angular resolution provided by the Australian SKA Pathfinder (ASKAP) and ultimately the SKA itself to study the physical and thermal structure of the Magellanic System throughout the halo, significant advances will be made in the next decade towards understanding the physical processes that are essential to feeding external material into galaxies. High accuracy proper motions of the Magellanic Clouds, together with HST stellar proper motions, will improve our understanding of the orbital history of the Magellanic Clouds and offer insight into future interactions of the Milky Way-Magellanic system. These will be obtained through long baseline interferometry measurements of the proper motions of masers in the LMC and SMC.

Another potential source of fuel for star formation is the extended gaseous halo around the Milky Way in the form of the so-called high velocity clouds detected in atomic hydrogen and their surrounding pool of ionized gas. Current accounting for the quantity of neutral gas shows clearly that it alone is insufficient as a source of fuel. However, there is likely some fraction of unaccounted for optically thick or molecular "dark gas" that may raise the total gas content within these clouds. Observations with the SKA towards the end of the next decade will measure that fraction. The high-velocity clouds provide an important set of test particles in the halo for measuring the physical properties, particularly temperature and density, of the halo. Surveys with ASKAP and SKA will provide clear measurements of these physical properties.

A significant fraction of the gas in the Galactic halo may also be attributed to the outflow of structures formed in the disk, but extending into the halo. Understanding how much of the halo's gas is supplied by the disk and how much returns to the disk is essential to understanding the life-cycle evolution of the Galaxy. During the next decade surveys of atomic gas with ASKAP and diffuse polarization from magnetized, ionized gas with MWA and Parkes will trace this interface between the Milky Way disk and its circumgalactic environment.

Underlying all knowledge of the properties of the halo, and critical to understanding the interaction of the Galaxy with the circumgalactic medium, is the nature of the magnetic field in the halo. Containing as much energy as thermal motions, magnetic fields can have a significant impact on how a system evolves. The next decade should see immense progress in the understanding of the magnetic field properties of the halo and circumgalactic gas, primarily through polarization surveys with ASKAP, but complemented with MWA and Parkes surveys of the diffuse polarized emission from the magnetized, ionized halo.

Requirements:

- High sensitivity and angular resolution observations of the atomic gas using ASKAP
- Long baseline interferometry for maser proper motions of the LMC and SMC
- High polarization purity and sensitivity observations with ASKAP
- Broad-bandwidth polarization surveys with the MWA and Parkes
- Significant involvement in the SKA phase 1 design and planning to guarantee that capabilities for measuring diffuse gas over large areas and high precision, broad-bandwidth polarimetry are available

What is the overall structure of the Galaxy and its magnetic field? Where are the halo, disk, spiral arms?

At the heart of humanity's quest for knowledge lies a desire to know about the environment in which we live. In spite of decades of study the overall structure of the Milky Way galaxy remains elusive, largely because of our embedded position within it. The full extent of the stellar and gaseous disks as well as the number and location of the spiral arms are still very poorly known. Furthermore, the stellar structure of the halo and Galactic bulge provide information about the evolution of the Galactic system.

Our knowledge of the structure of the Galaxy is set to change dramatically over the next decade. A significant change will be the GAIA satellite, which will provide millions of stellar distances to 10 kpc at 10% precision, together with proper motions of 1 km/s precision to a distance of 20 kpc. Australian astronomers will provide complementary information to GAIA about the spiral structure of our Galaxy through parallax measurements of maser emission. The Long Baseline Array (LBA) will be used to measure parallax distances to several hundred locations within the Galaxy, which will complement well other ongoing surveys conducted with the VLBA and VERA. Toward the end of the decade SKA1-mid, as part of an intercontinental VLBI array will enable the efficient measurement of trigonometric parallax toward several hundred more, providing accurate distances to the spiral arms which is critical for determining spiral structure.

The precision parallax measurements of stars and star-forming regions will complement dense and diffuse gas tracers to provide full maps of the gaseous spiral structure the Milky Way. These maps will require large-scale, high-resolution surveys of diffuse gas tracers, such as HI, and molecular gas tracers, such as CO and NH_3. Finally, determining parallaxes and model-based distances to pulsars using large radio telescopes, such as Parkes, will add to this wealth of information and will help build up a detailed map of the spiral structure of the Milky Way.

A critical component in understanding Galactic structure is determining the structure of the disk magnetic field and whether it follows spiral arms and how it might be linked to the halo. The magnetic field structure of the disk and halo can be derived through multiple complementary methods. Faraday rotation studies of pulsars enable tomographic mapping of the large-scale Galactic magnetic field and its strength. Faraday rotation measurements of both pulsars, which are embedded within the disk, and extragalactic radio sources, which are located behind the disk, provide density-weighted measurements of the magnetic field strength integrated along the line-of-sight. The POSSUM survey planned for the next decade on ASKAP will make use of this technique towards extragalactic sources to derive the magnetic field strength and geometry of the disk, halo and its interface. Parkes observations, especially if enhanced with an ultra-wideband receiver, will enable frequency diversity in large-scale surveys of the polarised Galactic background and will provide a large increase in the number and accuracy of pulsar rotation measures. A complementary technique makes use of Zeeman splitting of radio spectral lines, particularly of OH maser emission, to measure the in situ magnetic field strength. This technique is being applied in the Galactic disk and could be extended if high spectral resolution polarimetry were available on ASKAP.

Requirements:

- Long-baseline interferometry at centimetre wavelengths for pulsar and maser parallaxes
- Precision, broadband polarimetric surveys with ASKAP and Parkes
- Wide-bandwidth observations of pulsar Faraday rotation using Parkes
- Large-scale surveys of HI and OH with ASKAP, and dense gas tracers with Mopra
- High spectral resolution, full polarimetric capabilities on ASKAP and ATCA for surveys of maser Zeeman emission

How are the building blocks of the Galaxy assembled?

The Milky Way has several basic components: the halo, bulge, thick disk, thin disk and star clusters (open clusters and globular clusters). Understanding the detailed evolutionary connections between these Galactic stellar populations is key to determining how galaxies are assembled. The goal of Galactic Archaeological research is to identify the original stellar structures that led to the present Galactic components by exploiting the motions and chemistry of stars.

While numerous key discoveries have been made in the previous decade, the high-impact breakthroughs in the next decade will come from large-scale surveys that are observed and analyzed homogeneously. Recently, a pioneering million star spectroscopic survey using the HERMES instrument commenced with the aim of identifying the stellar building blocks of the Galaxy. With ~25 chemical element abundances per star, it will provide a gold mine for discoveries relating to the assembly history of the Galaxy. Support for the AAT and HERMES instrument over the next decade is vital to reap the benefits of the infrastructure established over the past decade. Furthermore, significant and on-going access to 6-10m class telescopes equipped with high resolution spectrographs will enable deep targeted follow up observations, and person power to develop novel techniques to derive precise chemical abundances are all critical for success.

Requirements:

- Dedicated large-field of view, high resolution spectroscopic capabilities on ~4m class telescopes, such as HERMES instrument on the AAT
- 6-10m telescopes equipped with high resolution spectrographs to enable deep, targeted follow-up observations

What is the life-cycle of interstellar gas and how does it impact on the formation of stars?

The evolution of the ISM is a constant interplay between heating provided by high-mass stars and cooling through metals. Understanding how matter heats and cools in the ISM helps reveal how molecular clouds form and what conditions are important for setting the initial conditions for star formation. The continual energy flow through the ISM and the interchange of materials between its gas and that in stars forms a cycle that drives the evolution of galaxies.

The ISM encompasses ionized, neutral and molecular environments with density and temperature contrasts of many orders of magnitude. It also contains a solid component - dust grains that can provide the seeds for both star and planet formation. Coursing throughout the ISM are cosmic-rays, which carry as much kinetic energy as other components of the ISM and play a significant role in astrochemistry. While the basic parameters of the ISM are known, the formation processes of clouds, both atomic and molecular, are unclear, and the key events, which determine when and how star formation occurs are contentious. Significant progress will be made in understanding the connections between these phases in the coming decade through observations that trace the material from the large scales traced by atomic gas (HI, neutral C), through newly formed molecular gas (such as OH), to CO and ultimately to the dense molecular gas that is intimately linked to the formation of stars on small-scales.

Our understanding of the evolution of the diffuse ISM will be transformed through surveys with ASKAP, which will explore the heating and cooling of HI throughout the Galactic disk and Magellanic Clouds. ASKAP surveys will probe HI from its warm, diffuse state through its more dense cold state and ultimately to diffuse molecular gas traced by OH. Connecting these surveys with observations of dense molecular gas tracers will help to establish whether the conditions in the diffuse ISM imprint onto star-forming molecular clouds. Gamma-ray production through collisions of cosmic-rays with the ISM and low frequency radio observations of free-free absorption offer new opportunities to map the density of cosmic-rays across much of our Galaxy. Following on the heels of the recently upgraded HESS-II system, the next generation TeV gamma-ray facility, CTA, is expected to reveal the localized diffuse gamma-ray emission.

At the heart of all processes in the ISM is the formation of new stars, the most influential are those with the highest masses (>8 solar masses) that dominate the flow of energy and the recycling of material. Despite the fact that these high-mass stars are the driver for the life cycle of our Galaxy, little is known about the detailed physical processes that drive the initial fragmentation of a cloud into the seeds for star formation or about the very earliest stages in their formation and evolution. With ALMA's new and remarkable capabilities, this field is on the cusp of a revolution. ALMA will allow us, for the first time, to peer into the cold, dense interiors of clouds where material is being assembled: ALMA will reveal the initial conditions for high-mass star and cluster formation. Indeed, early science observations from ALMA's cycle 0 are already providing important constraints for models of these processes. ALMA observations of cluster-forming clumps in a range of environments within the Galaxy will identify the role environment plays in setting the necessary conditions for fragmentation and subsequent star formation. These new observations must be complemented by a coordinated theoretical and numerical modeling effort in order to characterize, understand, and explain the wealth of information they will provide.

Characterizing the earliest stages in the formation and evolution of high-mass stars can be achieved through observations of maser emission. Masers are powerful signposts of star formation and provide important information on both the kinematics and physical conditions of the gas surrounding a recently formed star. The presence and absence of different types of masers pinpoint particular phases in the evolution of a high-mass star. Over the next decade results form surveys such as SPLASH on Parkes, and MALT-45 on the ATCA and GASKAP on ASKAP will refine and improve their utility in understanding the conditions within the gas as stars form and evolve.

Requirements:

- Parkes/ASKAP (HI, OH), HEAT/NANTEN2 (C, C+), Mopra (3mm molecular tracers), ATCA (12 and 7mm molecular tracers)
- High spatial resolution, high dynamic range, high sensitivity mm observations using ALMA
- Formal collaboration with the Chilean astronomical community through joint postdoctoral fellowships
- Gamma-ray telescopes (HESS-II, CTA)
- World-class supercomputing facilities for theoretical modeling

What is the origin and evolution of elements in the early Universe? Are there any surviving Pop III stars to the present day?

Understanding the origin and evolution of the chemical elements is fundamental to understanding the Galaxy. The so-called "Population III" stars are the earliest stars in the Universe, formed from pristine material with Big Bang elemental distributions, having no metal content. The most metal-poor star known to date was recently discovered using the SkyMapper telescope and has an iron content of at most 0.0000001 of the Sun. Identifying and characterizing such extremely metal poor stars provide vital insights on Big Bang nucleosynthesis by comparing their light element abundance ratios against what is predicted. These comparisons are essential to understand how chemical enrichment proceeded within the Galaxy by matching the observed abundances with the types and rates of supernova explosions and other material feedback mechanisms. In turn this provides information on the nature of stars that formed in the early universe.

Over the next decade as more discoveries are made, development of a robust theory of star formation to understand the underlying physics will likely emerge. Currently five extremely metal poor stars have been identified, with Australian astronomers leading the discovery of four. Over the next decade, dedicated large field-of-view, narrow band imaging capabilities and high-resolution spectroscopic capabilities with high efficiency are needed to make the necessary breakthrough discoveries. Imaging capabilities are currently available in state-of-the-art facilities like the SkyMapper telescope and significant and on-going access to 6-10m telescopes equipped with high resolution spectrographs are needed to provide the key spectroscopic follow up.

Australian astronomers will provide key insights into the origin of the heavy elements in the early Galaxy. Considerable progress will be made in refining theoretical models to address uncertainty in stellar yields. In particular, our understanding of stellar convection, a major source of uncertainty for many decades, will benefit from multi-dimensional simulations using supercomputers. Supercomputers will also help address the role of stellar rotation and magnetic fields, as well as non-convective mixing processes, all of which can affect stellar yield calculations for stars of all masses including those that explode as supernovae. Finally, current stellar yield calculations are for single stars, however, binary interactions are known to significantly affect stellar evolution and stellar yields. The details of these interactions will be determined in the next decade. Further investment in people to develop theoretical research is essential for success.

Requirements:

- Dedicated large-field of view, high resolution spectroscopic capabilities on ~4m class telescopes, such as HERMES instrument on the AAT
- Wide field-of-view imaging capabilities, as enabled through SkyMapper
- 6-10m telescopes with high-resolution spectroscopic capabilities, possibly via the Maunakea Spectroscopic Explorer (MSE)
- Supercomputers, to allow advances in modeling star formation and stellar astrophysics

Australia's Role

Australian astronomers and Australian facilities will have a variety of roles in answering these questions. In some cases we expect to lead large-scale international research projects, in others we will be contributors to internationally led projects. In other cases our facilities may be essential, but have limited Australian involvement in the actual research. We summarize below the areas where we expect Australian astronomers will play a key leadership role and those area in which Australian astronomers will likely contribute via international collaborations.

Areas where Australian astronomers will play a key leadership role are:

- Deep, large-scale surveys of the interstellar medium including HI & OH (ASKAP then SKA-1), magnetic fields (ASKAP & MWA), C/C+ (Antarctic THz telescopes), and CO (Mopra)
- Surveys which probe the building blocks of the galaxy using HERMES/GALAH and Skymapper
- Theoretical work on the chemical evolution of stars
- Targeted studies of the earliest phases of star formation using ALMA
- Pulsar Faraday rotation and timing observations with Parkes

Areas where Australian astronomers will be a significant player in international collaborations are:

- Theoretical work exploring molecular cloud through to star formation
- Galactic and extra-galactic studies using ALMA
- Galactic spiral structure using maser parallaxes

Requirements

Capabilities

The required capabilities cover a broad range in both wavelength coverage and technique – it is the combination of all of these capabilities that will provide Australian astronomers with the necessary tools to address the key science questions. In Table 1 we summarise the key science questions identified above and the capabilities that will be required to answer them.

Table 1 : The key science questions and the capabilities that are required to answer them.

Science questions	Capability						Wavelength coverage							Theory
		Spatial resolution												
	widefield	high	Very high	High spectral resolution	High dynamic range	Polarization	m	cm	mm	THz	IR	optical	high-energy	
How does the Galaxy interact with its circumgalactic environment? What are the physical properties, including magnetic configuration, of the halo?	x					x	x	x					x	x
What is the overall structure of the Galaxy and its magnetic field? Where is the halo, disk, spiral arms?	x	x	x			x	x	x	x	x		x	x	x
What is the life-cycle of interstellar gas and how does environment affect star formation?	x	x		x				x	x	x			x	x
How are the building blocks of the Galaxy assembled?	x	x		x							x	x		x
What is the origin and evolution of elements in the early Universe? Are there any surviving Pop III stars to the present day?	x	x		x							x	x		x

Facilities

The facilities that are required to provide the capabilities listed above are located both within Australia and abroad. Some of these facilities require significant financial and logistical support from the Australian community, while others can be accessed through strategic collaborations with international colleagues. In Table 2 we list the facilities expected within the 2016 – 2025 period that provide the necessary capabilities to address our key science questions.

Listed below are our priority rankings of these facilities (the letters in Table 2 reflect this ranking). Facilities ranked as "A" are those that are likely to provide the highest impact science over the coming decade. Those facilities ranked as "B" are valuable as standalone facilities and will also play important complementary roles for A-ranked facilities, either through their capabilities or wavelength coverage.

Recommendation for the prioritization of support for facilities for the period 2016 – 2025:

A. Optical/IR telescopes (SkyMapper, AAT, 8-m access), transitioning to an ELT
A. SKA precursor m-/cm-wave telescopes (ASKAP, MWA), transitioning to the SKA
A. Cutting edge mm-wave telescope (ALMA)

B. High-performance computing facilities (Pawsey, NCI)
B. Complimentary cm telescopes (ATCA, Parkes, LBA)
B. mm/THz survey telescopes (Mopra, NANTEN2, HEAT)
B. High-energy telescopes (HESS-II)

Table 2: The required facilities, listed in order of increasing wavelength, needed to provide the key capabilities.

Facility	Capability						Wavelength coverage							Theory
		Spatial resolution												
	widefield	High	Very high	high spectral resolution	High dynamic range	Polarization	m	cm	mm	THz	IR	optical	high-energy	
HESS-II	B												B	
SkyMapper	A	A										A		
HERMES on AAT	A	A		A							A	A		
8m telescope (MOS)		A		A							A	A		
HEAT	B			B						B				
NANTEN2	B			B					B	B				
ALMA		A	A	A	A	A			A	A				
Mopra	B			B					B					
ATCA		B		B		B		B	B					
LBA			B					B	B					
Parkes	B			B		B		B						
ASKAP	A				A	A		A						
MWA	A				A	A	A							
HP computing	B	B		B	B			B	B		B	B		B

Looking forward

While this decadal planning process must focus on capabilities and facilities that will be available during the 2016-2025 period, we must also position ourselves to be key players in the development and planning around next-generation telescopes, such as the ELTs/GMT, SKA, DATE5, MSE and the CTA. The top 2 A-ranked facilities listed above provide direct links to the next-generation telescopes and by exploiting these facilities over the next decade, the Australian community will be well placed to play leading roles in the development of the next-generation telescopes.

Strategic collaborations

The potential exists for strengthening and building new international collaborations that are strategically important. In particular, we have identified the following international communities through which formalized collaborative links will be strategically important for our research.

- Multi-national SKA collaboration – to inform and participate in the SKA design and construction
- Chilean community – to enable collaborative access to their telescopes, including ALMA
- Japanese and German community – to explore options for external funding of Mopra, and to enable continued access to NANTEN2
- Chinese community – to improve access to and the ability to influence the design goals of FAST
- Chinese community – to provide continued access to HEAT and to develop key partnerships for DATE5

Summary

Australia has a long, proud history in Milky Way science fuelled by our geographic advantage as well as our strengths in survey science, which is essential to studies of our Galaxy. Our expertise and the importance of this research will increase over the next decade as Galactic Archeology surveys continue, the cool Universe is revealed by ALMA, and the world's most powerful radio telescope, the SKA, is built and begins routine observing. Indeed, over the next decade our role in Astrophysical research must evolve as these new telescopes provide sufficient resolution to conduct detailed studies in the nearby Universe. Galactic science will play an essential role in the next decade by providing the underpinning context to answer questions of broad astrophysical context like: How did the first stars form? What galactic conditions affect star formation? What is the structure of the Galaxy? and How do galaxies interact with their surroundings? Over the next decade this research will not only reveal the details of these processes in our home galaxy, but will also underline its importance for the understanding these processes more broadly, by asking and answering the same questions that are pursued in the extragalactic context.

Appendix: Working Group 1.3 Membership

Jill Rathborne (CO-CHAIR)
Naomi McClure-Griffiths (CO-CHAIR)
Gayandhi de Silva (Executive team member)
Christoph Federrath (Executive team member)

Alex Hill
Amanda Karakas
Andrew Walsh
Anne Green
Bryan Gaensler
Chris Tinney
Cormac Purcell
Daniela Carollo
Ettore Carretti
Gary Da Costa
Gavin Rowell
Geraint Lewis
Joanne Dawson
John Dickey
John Lattanzio
Joss Hawthorn
Ken Freeman
Martin Asplund
Michael Ashley
Michael Burton
Nick Tothill
Ryan Shannon
Shari Breen
Simon Ellingsen
Xiaohui Sun
Yanett Contreras