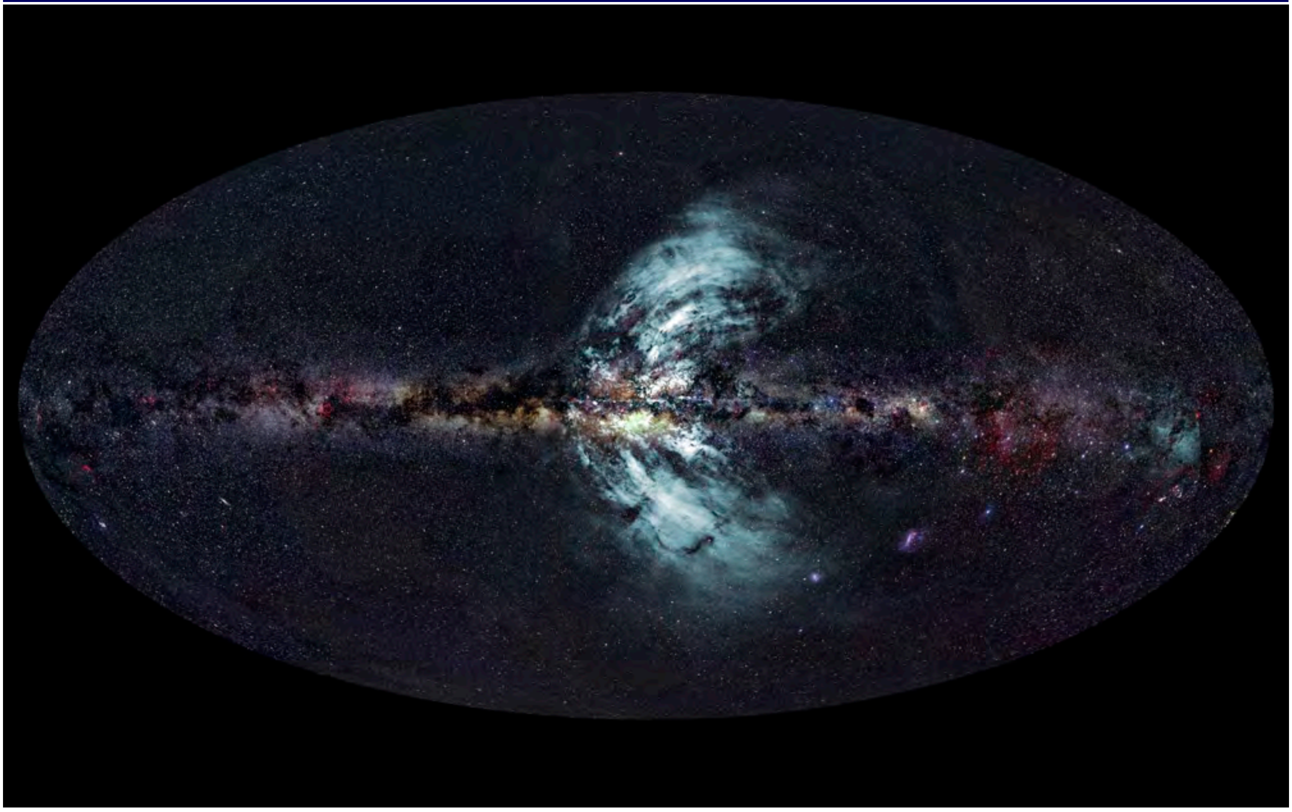
High Energy and Fundamental Astrophysics



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EXECUTIVE SUMMARY

Working group 1.4, "High energy and fundamental astrophysics" is focussed on objects and phenomena characterised by **extreme physical conditions**, including black holes, neutron stars, and the accretion disks that typically surround these objects; supernovae and their remnants; cosmic rays and neutrinos; and more. Key science questions for the next decade include:

- How and where are cosmic-rays accelerated to extreme energies?
- How are outflows from compact objects accelerated, and how do they evolve?
- How best can we exploit gravitational waves to explore the universe around us?
- Is our understanding of gravity correct?
- How do pulsars shine? What makes up the cores of neutron stars?
- What is the nature of dark energy and dark matter?
- What is the nature of fast radio bursts, and what can they tell us about cosmology?
- How do stars collapse into black holes or neutron stars, and what are the multi-messenger signatures of these events?
- What determines how fast black holes spin, and what impact does spin have on their radiative and mechanical power output?
- What is the origin of heavy elements and how do cosmic explosions forge them?

In order to address these questions within the next decade, we recommend the following:

- Maintain or upgrade local radio observational capabilities to support pulsar observations
- Further develop experimental and observational capabilities for gravitational-wave astronomy to take advantage of the expected first detection
- Maintain access to international ground-based high-energy and gravitational wave observatories by supporting existing collaborations
- Develop high-energy and fundamental theory as a critical resource supporting local and international observational efforts
- Develop time-domain astronomy via dedicated Australian facilities, as well as support for existing facilities and strategic involvement of international observatories
- Maintain experimental and observational capability in nuclear astrophysics
- Further develop galaxy surveys, simulations and cross-disciplinary tools to boost dark matter and astroparticle physics

Contents

1 SUMMARY

Members of working group 1.4, "High energy and fundamental astrophysics", are focussed on observational and theoretical studies of objects and phenomena characterised by **extreme physical conditions** (temperature, density, magnetic fields). These objects include black holes, from stellar mass objects in binaries, to the supermassive giants at the centre of active galaxies; neutron stars, from rotation-powered pulsars through accretion-powered pulsars and magnetars; accretion disks; supernovae and their remnants; regions of particle acceleration, and the cosmic rays they produce; and more. A substantial fraction of the group members have as their priority development of **new observational methods** for astrophysical objects, including very high-energy gamma-ray astronomy, neutrino astronomy, and gravitational wave astrophysics. Many of the observational efforts are dedicated to transient phenomena which cannot be predicted in advance. As a result, these activities offer significant opportunities for new and unexpected discoveries, which may provide the highest scientific return.

The science objectives which are priorities for the group include some of the most fundamental questions of physics and astronomy, long recognized as national and international priorities, including

- How and where are cosmic-rays accelerated to extreme energies?
- How are outflows from compact objects accelerated, and how do they evolve?
- How best can we exploit gravitational waves to explore the universe around us?
- Is our understanding of gravity correct?
- How do pulsars shine?
- What makes up the cores of neutron stars?
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The Australian high-energy and fundamental astrophysics community has broad research interests with a high level of international engagement. We identify here three primary issues which should be addressed in the upcoming decadal plan.

- **Links to international facilities** Several of the areas in WG1.4 rely to a large part (or entirely) on international facilities. There are frequently requirements for regular funding to support membership; provide personnel for service observing; or provide upgrades. These funding requirements are typically met by University or ARC funding, but the latter schemes in particular are not well suited to such demands. A key issue for researchers in this working group is how to improve the stability of "subscription" funding and how to engage with future projects

- **New International opportunities** There are new opportunities emerging in several areas (CTA, aLIGO) that may demand strategic investment. These opportunities are being pursued by individual groups, which has in the past worked poorly when the required funding has exceeded the typical University/ARC Discovery Project funding envelope. These larger opportunities should be assessed at a broad, national level, in the same manner as (e.g.) international 8-m telescope access.

- **Transient multimessenger astronomy** Many of the events and phenomena of interest to this community are explosive transients that are unpredictable. Several Australian facilities play key roles in multiwavelength followup campaigns on a variety of objects. Australia is a key location for several instruments that are part of world-wide networks of wide-band transient followup networks (ROTSE etc.). Yet no dedicated local projects are carried out here. This field has seen rapid growth over the last decade, and the lack of national investment may see a significant opportunity cost for Australian astronomy.

Below we present a summary of the complete working group report, divided into the following sections.

Ground-based high-energy astronomy addresses science goals including the search for the origin of cosmic rays (up to 10^{20} eV), and the mechanisms by which cosmic-rays and electrons are accelerated to such energies. In Australia this area incorporates VHE gamma-ray (see §3), cosmic ray and neutrino (§4) observations, carried out via collaboration with major international observatory facilities, including the recently upgraded High-energy Stereoscopic System (HESS) in Namibia; the Pierre Auger observatory in Argentina; and the IceCube observatory in Antarctica. These instruments cover the highest-energy gamma rays (HESS), cosmic rays (Auger) and neutrinos (IceCube) from astrophysical sources. This effort is led primarily by the University of Adelaide, but there are significant links to local theorists, as well as observational capabilities in other wavebands (particularly mm-wave). These instruments can also serve as key components for future multiwavelength transient followups.

The Auger cosmic-ray observatory is planning a substantial (US$12m) upgrade beginning in 2015, with new detector installations to improve the cosmic ray mass and charge measurements. IceCube will also be upgraded over the next decade, to provide increased sensitivity.

The planned next generation VHE gamma-ray instrument, the Cerenkov Telescope Array, will commence its pre-construction phase in the next 2–5 years. The total expected cost for the northern and southern telescope sites is €200m. This instrument will offer sensitivity in excess of ten times that of HESS, and improved angular resolution. A consortium of six Australian universities joined CTA as an associated party in 2013, and full membership will require a contribution to the construction and operation costs, with an initial investment of $500k.

Funding to support these activities is primarily via Universities and ARC. Continued activity in the Auger collaboration will require contributions of $200k towards the imminent upgrade. Subscription costs for the HESS, Auger and IceCube collaboration are at the level of $10–40k per annum. While existing funding sources have proved adequate to maintain these collaborations in the past, they do not offer stability over the decade-long timescale necessary to provide ongoing opportunities.

Recommendation: The astronomical community should support ongoing involvement in ground-based high-energy astrophysics, via strategic collaboration with international facilities, as well as complementary "multi-messenger" collaborative links with national facilities. Subscription costs to international ground-based high-energy observatories should be considered for funding under any successor to NCRIS. In the long term, upgraded and new instrumental capabilities should be strategically assessed for opportunities to leverage existing expertise.

Nuclear astrophysics is concerned with the detailed processes by which elements are synthesized and recycled in stars, compact objects, and supernovae (see §5). This research area has grown dramatically over the last decade, and is now represented by active groups studying stellar evolution over the entire mass range, from the lowest to the highest mass stars, supernovae, explosive nucleosynthesis, and formation of compact remnants, as well as thermonuclear bursts (via numerical modelling and X-ray observations). The new HERMES instrument on the AAT is one of the key Australian instruments to study nucleosynthesis. Experimentally, the AMS facility at ANU has recently begun to be used for studying the isotopic composition of pre-solar grains, in collaboration with astrophysicists at ANU and Monash.

Funding support for these activities has been via the universities and the ARC. There exist further opportunities to develop AMS for astrophysics. More substantial opportunitites exist via collaborations with international facilities where a wider range of experimental capabilities are available.

Recommendation: Local observational and experimental facilities including HERMES and AMS, as well as adequate supercomputer access are a key resource for this community. Strategic funding should also be secured to maintain access to international collaborations, where existing funding sources are not sufficient or suitable.

Dark Matter is inferred to make up the bulk of the mass in the universe, from cosmological studies as well as galactic structure and dynamics, and a number of direct detection experiments have emerged in recent years, although so far without unambiguous success (see §6).

Australian activity in this area has benefited over the last decade from extensive observational surveys and simulation efforts, with the primary goal of understanding galactic formation and evolution over cosmic time. Local instrumentation such as SAMI are a world-leading resource, and researchers exploit a number of approaches, including cosmological microlensing, peculiar velocity studies, and innovative new approaches such as "direct shear mapping". Simulations also play a key role, and new synergistic resources including the Theoretical Astrophysical Observatory will likely play a growing role in this area in the future. Involvement in direct detection experiments is minimal, although conflicting results from existing experiments motivate further work, and a southern hemisphere instrument could help to resolve claimed annual modulation signals.

Recommendation: Current and future large-scale galaxy surveys and simulations are a key enabler for dark matter studies, and should be encouraged in order to address the science questions in this area. Further development of computational tools such as TAO, and encouraging new links between the cosmology and particle physics communities will likely result in substantial science return.

Pulsars have proliferated over the last decade as laboratories in which to make increasingly high-precision tests of general relativity, as well as alternative theories (see §7). Additionally, assemblies of these objects have been exploited as "pulsar timing arrays" (PTAs) with which to detect (or constrain) very low-frequency gravitational waves.

Australia plays a very significant role internationally in observational and theoretical pulsar science, and this arises in part from the availability of excellent local facilities, notably the Parkes 64-m radio telescope. The wide frequency coverage and precision polarisation capabilities of the Parkes telescope will be required for precision timing projects into the SKA era. In the long-term, the SKA will provide orders-of-magnitude improvements in our capabilities for pulsar science. Within the next decade, mid-scale national facilities including MOST (currently being upgraded to include a pulsar monitoring backend) and the MWA will significantly add to local instrumental resources. The South-African SKA precursor MeerKAT, expected to be operational with all 64 antennas by 2016, and the Chinese FAST radio telescope, expected to be operational in 2018, will also serve as high sensitivity pulsar telescopes.

Recommendation: Prior to SKA operations, maintaining and upgrading Parkes is the highest priority for pulsar science. The proposed UWB receiver for Parkes will enable the highest precision pulsar timing measurements, essential for PTA projects, and complementary to MeerKAT timing efforts. Upgrades to MOST and development of MWA pulsar capabilities should also be seriously considered.

Gravitational-wave astrophysics offers enormous potential in the coming decade. Gravitational waves are vibrations in spacetime that propagate at the speed of light, and are produced by violent events and/or massive objects including binary neutron star mergers, supernovae, rapidly-rotating neutron stars, and supermassive black holes. These waves propagate freely through the Universe, and offer a categorically new way to obtain information about the Universe around us. Pulsar timing arrays are sensitive to gravitational waves at very low (nHz) frequencies. The primary sources for these waves are binary supermassive black holes in distant galaxies. The Parkes PTA project has generated the world's best PTA data set and analysis of these data has already placed a limit on the strength of the nHz gravitational-wave background that eliminates some models for the formation and growth of supermassive black holes in the early Universe.

Complementing the efforts at nHz frequencies with pulsar timing arrays, and proposed space-based instruments at mHz frequencies, is the world-wide interferometric network. This network presently comprises the Laser Interferometric Gravitational-wave Observatory (LIGO) in the US, and the Virgo detector in Europe. These interferometers are sensitive to gravitational waves in the 10 Hz – kHz range, and have been operational over the last few years in a preliminary phase which has clearly demonstrated their technical feasibility. Two additional interferometers will be built in the coming decade; KAGRA in Japan and LIGO-India with slightly better sensitivites than the Advanced LIGO instruments.

These instruments are currently undergoing upgrades prior to an "advanced" phase of operation, with roughly 10-fold increase in sensitivity, which are widely expected to provide the first detection of gravitational waves once observations commence, in 2015. Commissioning of the advanced detectors is ahead of schedule. Members of the Australian community are actively contributing to theoretical and experimental efforts to improve the instrumental sensitivity, as well as carrying out optical and X-ray measurements to facilitate gravitational wave searches. Several groups are also planning for electromagnetic followups to the expected gravitational wave triggers, with memoranda of understanding signed between LIGO and five Australian observatories. An expansion of local resources and expertise in multimessenger and gravitational-wave astrophysics is required to contribute significantly to complementary and followup electromagnetic observations, and strategic opportunities here should be exploited. Critical for maximal scientific return in this aspect is the development of partnerships with other observational communities to fully realise the goal of genuinely "multimessenger" astrophysics.

In the long-term, optimal localisation with interferometric detectors will necessitate a southern-hemisphere instrument, and Western Australia has already been identified as a suitable site. Planning has already commenced for a third-generation instrument, ET, which would complement the current instruments once gravitational waves have been detected.

Recommendation: Australia should maintain and grow its existing capabilities in interferometric gravitational-wave astronomy, including experimental design and development of advanced-phase interferometric detectors such as Advanced LIGO, KAGRA and LIGO-India, in addition to complementary efforts to pursue gravitational wave detection via pulsar timing arrays. For the long-term, Australia should also continue to provide design input to future instruments including LISA and ET.

Theoretical high-energy astrophysics supports, informs, and leads much of the observational efforts described here. Australian high energy theorists focus on accretion processes in AGN, and consequent outflows; the interaction between Galactic ISM and outflows; the interior structure and properties of neutron stars; non thermal phenomena (such as particle acceleration and non-thermal emission processes) and ultra high energy cosmic rays. Five Australian universities have significant investment in theoretical astrophysics, in terms of personnel, numerical codes and computing infrastructure (see §9). Continued investment in theoretical astrophysics — not usually seen as a priority for large observational programs — is an ongoing priority for this community. This working group endorses the Australian National Institute for Theoretical Astrophysics (ANITA) Strategic Plan 2012-2015, including the formation of a *National Theory Centre*.

Recommendation: University departments and observatories should take the opportunity, when possible, to appoint excellent theoretical high energy astrophysicists, who are capable of significantly contributing to Australian and international programs in this discipline and who can also add value to the observational programs. Theoretical high energy astrophysics also requires a substantial investment in supercomputing resources and we recommend that this be maintained at *at least* the current level in the National Computational Infrastructure, the Swinburne Centre for Astrophysics and Supercomputing and the Pawsey Centre.

Time-domain and multimessenger astrophysics are pervasive aspects of the science interests of this working group. Transient sources arise from the highest energy density events in the universe, and frequently demand time-constrained observations in multiple electromagnetic bands (see §10). Dramatic growth in transient (time-domain) astrophysics has occurred over the last decade, motivated in a large part by increasing CPU power and digital storage capability with vastly reduced costs. It is now feasible for wide-field robotic telescopes to scan the sky continuously, feeding automated pipelines that detect new sources and immediately inform the observers to allow source characterisation and detailed followup.

Australia's southern location offers particular opportunities for wide-field astronomy. This has been acknowledged indirectly by the development of world-wide networks including instruments in Australia (e.g. ROTSE, CADOR, HATNet). These opportunities can be expected to increase in the future, with a growing rate of triggers generated by a larger and larger stable of instruments world-wide, not least the prospect of gravitational wave detections.

At the same time, prompt and effective characterisation of new transients may require co-ordinated followup in two or more wavebands (see §11). We see it as highly desirable that Australian observers have access to instrumentation at all possible wavelengths to enable such followup. This goal will require a mix of strategies. Australia already offers world-leading resources for radio observers, and thanks to the development of SKA and its precursors, will continue to do so for the next decade. For other bands, the situation is more complex. 8-m class telescope time at overseas facilities is a broad-scale national priority, and those in this community wishing to exploit those resources for transient followups may have the opportunity to do so via national agreements. Ground-based high-energy facilities can be accessed via local collaborations with international-scale instruments, as pursued by U. Adelaide. X-ray telescopes are generally operated on a Guest Observer (GO) basis open to proposals from observers from any country. There remain issues with access to these instruments; the pool of local experienced observers may be small (or non-existent); open access models are not guaranteed. Thus, the ability of local observers to carry out multi-messenger astronomy are not guaranteed.

Recommendation: A national strategic assessment of Australian-based opportunities in time-domain astronomy should be undertaken. Such an assessment may indicate the need for national-level investment in suitable instrumentation that will leverage our geographical position and instrumentation in other bands to provide excellent science return. This assessment should also consider the goal of maintaining access to overseas instruments (other than 8-m optical telescopes) that are seen as critical to this and other research areas. Dedicated memoranda of understanding may be adopted (as with the recent CAASTRO-eROSITA agreement) which may improve the prospects.

2 BACKGROUND

Working group 1.4 is inspired by IAU Division D, "High Energy Phenomena and Fundamental Physics"[1]. As with that division, the group draws from

> …a broad scientific perspective including, e.g., multi-messenger astronomy (cosmic rays, neutrinos, gravitational waves, etc.), and non-thermal phenomena emitting radiation from the radio to TeV gamma-rays. [Research] interests span from the mildly-relativistic electrons of supernova remnants or the hot intracluster medium, to ultra-relativistic cosmic-rays and their products in active galaxies and elsewhere. Phenomena include plasma astrophysics, magnetohydrodynamics, shocks, particle acceleration, photoionization, jets, outflows, bursts, extreme gravity, strong magnetic fields, etc. Example questions of topical interest might include the physics of dark matter, active galaxy feedback, missing baryons in the warm/hot phase of the intergalactic medium, and the equation of state of neutron-star matter.

[1] http://www.iau.org/science/scientific_bodies/divisions/D

The reporting criteria were based on the terms of reference given by the National Committee for Astronomy, and described at the Decadal Plan website[2]. We address these criteria under the following headings:

- Progress against objectives (in the previous Decadal Plan[3])
- Stocktake of (current and future) capabilities/resources (in the area)
- New (national or international) opportunities/requirements (in the area over the period 2016-25)
- Suggested strategies and resourcing levels (required to maximise these new opportunities)

This report is structured as follows. The first seven sections are delineated along waveband and/or thematic lines, and include contributions from the executive group members listed below:

1. Gamma-ray astrophysics *Gavin Rowell* (U. Adelaide)
2. Cosmic rays & neutrinos *Bruce Dawson* (U. Adelaide)
3. Nuclear Astrophysics *Alexander Heger* (Monash)
4. Dark matter *Katie Mack* (U. Melbourne)
5. Pulsars *Matthew Bailes* (Swinburne)
6. Gravitational wave astrophysics *Andrew Melatos, & Bram Slagmolen* (U. Melbourne) & *Paul Lasky* (Monash U.)
7. Theoretical high-energy astrophysics *Geoff Bicknell* (ANU)

Based on the input of the other executive members, we have also assembled two further sections, "Time-domain astrophysics" and "Multi-messenger astrophysics". These sections comprise input in the following areas:

1. X-ray observations *Paul Nulsen* (CfA)
2. Radio/sub-mm observation *James Miller-Jones* (Curtin)
3. Survey science *Eric Howell* (UWA)
4. Optical/IR observations *Roberto Soria* (Curtin)

[2] http://australianastronomydecadalplan.org

[3] New Horizons – A Decadal Plan for Australian Astronomy 2006–2015 (2005) http://science.org.au/natcoms/nc-astronomy/decadalplan.html

3 GAMMA-RAY ASTROPHYSICS

Gamma-ray techniques span the upper energy range of the X-ray band, to TeV (10^{12} eV, equivalent to $\approx 10^{-7}$ J) energies. These ultra-high energy (UHE) photons do not reach the surface of the Earth, but can be detected either by space-based instrumentation, or the imaging air Cerenkov (IAC) technique with ground-based optical telescopes. A prime motivation for TeV gamma-ray astronomy has been the search for the origin of Galactic cosmic-rays up to PeV (10^{15} eV) energies. Acceleration sites are expected to also be sources of gamma-rays, but until recently the connection between the purported sources (e.g. supernova remnants) has not been clear. Another significant class of gamma ray sources that has emerged over recent years are millisecond pulsars, with many known and new sources detected with the *Fermi*-LAT[4] via their gamma-ray pulsations.

Australia's primary involvement in gamma-ray astronomy is via the University of Adelaide[5], and their membership of the High-Energy Sterescopic System (HESS[6]), collaboration, the major southern hemisphere project in TeV gamma-ray astronomy. The HESS experiment is an array of four 13 m and one 28 m diameter (H.E.S.S. II) Atmospheric Cherenkov Telescopes (ACTs) located in the Khomas Highlands of Namibia (1). It is a collaboration of more than 170 scientists, from 32 scientific institutions and 12 different countries. The experiment detects very-high-energy (VHE) γ-rays in the range 100 GeV to 50 TeV. Adelaide's research has centred on Galactic high energy sources such as supernova remnants and pulsar wind nebulae. In recent years, HESS has continued to reveal new Galactic and extragalactic TeV gamma-ray sources, cementing TeV gamma-ray astronomy as a mainstream activity in this field. New potential classes of TeV sources such as massive stars and/or their clusters, starburst galaxies and compact binary systems have been identified, posing challenges to our understanding of particle acceleration processes covering a wide range of stellar evolutionary cycles.

Beyond Adelaide-led activities, a measure of the impact of gamma-ray astronomy on other Australian radio astronomical activities can be gauged by looking at the number of Australia Telescope Compact Array[7] (ATCA) and Parkes observation proposals in recent years. A search for the keyword 'gamma' in proposal abstracts using CSIRO-CASS's OPAL engine reveals 31 ATCA and 21 Parkes proposals since 2011 (most of which contain Australian authors), indicating a healthy interest in gamma-ray astronomy. The majority of these proposals relate to results in the MeV-GeV gamma-ray energy regime which will be discussed below (five ATCA proposals were linked to TeV gamma-ray results). There are also obvious links to X-ray astronomy and particle astrophysics as part of broader multiwavelength astronomy capabilities.

[4] http://www-glast.stanford.edu

[5] http://www.physics.adelaide.edu.au/astrophysics/gpr/research.html

[6] http://www.mpi-hd.mpg.de/hfm/HESS

[7] http://www.narrabri.atnf.csiro.au

3.1 Progress against objectives

Gamma-ray astronomy was identified in the Mid-Term Review of the previous Decadal Plan as a "New and Emerging Research Area". The Mid-Term Review recommended that participation in HESS/HESS-II should continue. A further recommendation was that funding should be sought to enable a consortium of Australia institutes to participate in the next generation ground-based gamma-ray telescopes (see §3.3).

Progress has been made in the search for the origin of PeV cosmic rays, with several old supernova remnants (SNRs) adjacent to molecular clouds identified as cosmic-ray sources (e.g 6). Energy-dependent TeV morphology has now been resolved in two pulsar wind nebulae (PWNe), clearly demonstrating their origin in high energy electrons and improving our understanding of pulsar environments over multi-parsec scales (5; 4). In the extragalactic realm, new constraints on the local ($z < 1$) infrared background radiation (a tracer of galaxy evolution) are also inferred. Increasing attention is also being paid to the many unidentified Galactic TeV gamma-ray sources. This class comprises about 30% of the Galactic population of over 80 sources today. Current ideas suggest these sources may represent old supernova remnants or pulsar wind nebulae (17; 16). See (14; 11) for recent reviews and the TeVCat[8] website for a list of sources.

The intimate astrophysics links between gamma-rays and the interstellar medium (ISM) have also enabled Adelaide to extend their activities into millimetre radio astronomy via observations with the Mopra and Nanten2 telescopes (see 8). For example, spatial correspondence of the dense molecular gas and TeV emission opens up the possibility to probe the diffusion properties of particles and magnetic fields inside interstellar medium clouds (12). The Adelaide group is also forging links with the Mileura Widefield Array[9] (MWA) radio telescope in the studies of transients, motivated by the potential of the new HESS-II system. The aim is to search for TeV gamma-ray counterparts to radio transients as the underlying non-thermal processes can be linked across the electromagnetic spectrum.

Exploitation of space-based gamma-ray instrumentation has primarily focussed on pulsars, understandable given Australia's historically leading role in this field. A number of Australian astronomers are active in using *Fermi*-LAT data in pulsar studies[10], as well as active galactic nuclei[11] (AGN) and unidentified sources (13). *Fermi*-LAT has rapidly expanded the MeV/GeV source catalogue to over 2000 examples. One of the most dramatic discoveries in recent years was the huge bi-lobal bubbles of GeV emission emanating from the central regions of our galaxy (15), which may signal past episodes of intense star formation activity.

[8] http://tevcat.uchicago.edu
[9] http://www.mwatelescope.org
[10] see http://www.atnf.csiro.au/people/Simon.Johnston/glast
[11] http://pulsar.sternwarte.uni-erlangen.de/tanami

3.2 Stocktake of capabilities/resources

The current HESS configuration, termed HESS-II, is an array of five telescopes using the ground-based atmospheric Cherenkov technique to image gamma-rays in the $\sim$20 GeV to $\sim$50 TeV energy range. An additional 28-m telescope was added to the original HESS array (four 12-m telescopes) in 2013. Routine operations (with all five telescopes) commenced in early 2014. The first science results are now available, and confirm the performance of the new 28-m telescope. These results are expected to be presented at conferences in mid-2014.

Two other successful instruments exploit the ground-based atmospheric Cherenkov technique at TeV energies – MAGIC[12] and VERITAS[13]. Both of these operate in the Northern Hemisphere. The angular resolution (68% containment radius for a point source) achieved by HESS-II, MAGIC-II and VERITAS is in the range 0.06 to $\sim$0.2 degrees, with instantaneous fields of view ranging from about 2 to 4 degrees (FWHM). These telescopes require cloud-free moonless nights to operate, and so have a duty cycle of about 10%.

The HAWC[14] observatory, to be completed in 2014, makes use of water tanks to induce Cherenkov light from air-shower particles. HAWC is based on the MILAGRO water pond detector which first demonstrated the potential of this technique by revealing a number of degree-scale TeV sources in the Northern hemisphere (2). HAWC will achieve an angular resolution of about 0.1 (> 10 TeV) to 2 degrees (0.1 TeV) but can operate with a nearly 100% duty cycle and close to 2π steradian field of view. A review of these techniques may be found in (10).

The space-based *Fermi* Large Area Telescope (LAT) is a solid-state silicon strip detector (akin to a spark chamber) designed to detect gamma-rays in the 100 MeV to 20 GeV energy range. *Fermi*-LAT data are publicly available within days. *Fermi*-LAT's angular resolution ranges from 0.1 (10 GeV) to about 3 degrees (100 MeV) and its field of view covers about one steradian. Access to *Fermi*-LAT data is straightforward via its Science Support Center website [15].

3.3 New opportunities/requirements

Current Instruments The currently operational ground-based instruments, including HESS-II, are expected to operate well into the 2016/2017 timeframe, and possibly longer depending on the level of upgrades applied (e.g. new camera detectors). The new lower energy threshold of HESS-II at $\sim$20 GeV has considerable overlap with *Fermi*-LAT, and offers new opportunities to probe transient phenomena such as gamma-ray bursts (GRBs) and X-ray binary flares, as well as pulsar magnetospheres. Vastly improved photon statistics are possible thanks to the HESS-II collection area, approximately 10^4 times larger than that of *Fermi*-LAT. Extensions to standard-model-physics related to cold dark matter is also a priority topic (7) given the recent

[12] http://magic.mpp.mpg.de
[13] http://veritas.sao.arizona.edu
[14] http://www.hawc-observatory.org
[15] http://fermi.gsfc.nasa.gov/ssc

detection of a ≈ 125 GeV feature in *Fermi*-LAT data, which HESS-II will certainly be in a position to verify.

The collection area advantage of HESS-II suggests that the ground-based detection of GRBs is just a matter of time, particularly given the *Fermi*-LAT detection of several > 30 GeV photons already from some GRBs (e.g. (3)). HESS-II will also offer improved performance (a factor up to $2\times$ better sensitivity and resolution) over HESS in the 0.1 to ≈ 10 TeV range. Thus, new opportunities for more detailed studies of known TeV sources will be available. In combination with ISM and magnetic field surveys (with e.g. Mopra, Parkes, MWA, ASKAP) these data will provide the first clear insights into particle diffusion properties and distribution of multi-TeV cosmic-ray accelerators in our galaxy. Although HESS-II is a private consortium, opportunities for target-of-opportunity (ToO) triggers, external observation proposals and multi-wavelength collaboration exist.

Future Instruments Over the next 2 to 5 years, the Cherenkov Telescope Array[16] (CTA) project will commence. CTA, by far the most prominent of the next generation design concepts, will comprise arrays of about 20 telescopes in the Northern hemisphere (concentrating on extragalactic science), and about 100 telescopes in the Southern hemisphere (concentrating on Galactic science). With a collection area of at least a few square kilometres, CTA is expected to be > 10 times more sensitive than HESS-II, and provide maps of the TeV gamma-ray sky at better than 0.05 degrees angular resolution. Despite the success of HESS-II et al., CTA will address a wide range of open questions associated with high energy sources. A detailed summary of the astrophysics potential from CTA can be found in (9).

For example, in conjunction with new ISM surveys, CTA's angular resolution and collection area will enable it to clearly distinguish between gamma-rays arising from cosmic-rays or electrons in our galaxy, probe variable TeV emission on sub-minute timescales, and observe unprecedented photon statistics from pulsar magnetospheres and transient events. Coupled with arc-minute scale maps of the ISM, CTA's performance will allow us to finally determine the level of cosmic-ray acceleration in young ($<$few 1000 yr) SNRs, which are thought to be responsible for the highest energy cosmic-rays coming from our galaxy, thus underpinning our understanding of the origin of Galactic cosmic-rays. The wide fields of view of many CTA telescopes (up to 9 degrees in diameter) will also enable extensive surveys of our galaxy and beyond. The all-sky coverage of HAWC will also perfectly complement CTA in the TeV band.

Prototype development (to the level of over €30m) for CTA has been funded from European/USA/Japan agencies. CTA will operate as a public observatory but a significant fraction of observation time will be held for the CTA consortium (the actual fraction is still under discussion). The total cost of CTA (north and south sites) is about €200m and so far has attracted membership of over 1000 scientists from over 20 countries. CTA is highly ranked (in similar terms to the Square Kilometer Array and the European Extremely Large Telescope[17], for exam-

[16] http://www.mpi-hd.mpg.de/hfm/CTA/CTA_home.html
[17] http://www.eso.org/sci/facilities/eelt

ple) in funding roadmaps of Europe, USA and Japan and is therefore quite likely to be funded. The benefits of CTA membership for Australia centre on the chance to influence the design of the array, to have commensurate access to 'CTA time' for observations, and, access to low-level data and cutting-edge analysis tools not available outside of the consortium (ie. to public 'guest observers). Australia's expertise in radio astronomy also places it in a unique position to lead major efforts in the multi-wavelength interpretation of CTA results.

Fermi-LAT is funded via NASA until 2015, and an extension until 2018 is currently under discussion. The space-based gamma-ray astronomy landscape beyond *Fermi*-LAT is somewhat less clear, with several future missions proposed. Three such missions are DAMPE[18], CALET[19] and GAMMA-400[20] which are designed to detect cosmic-rays, electrons and gamma-rays. Their gamma-ray energy coverage is designed to extend up to $\sim$10 TeV.

3.4 Suggested strategies and resourcing levels

Presently the Adelaide group (one tenured staff, average five PhD students) is the only one formally working in observational TeV gamma-ray astronomy. Ongoing membership of HESS-II requires of order $5k per post-doc and above (subscriptions for annual running costs) plus costs associated with observation trips to Namibia and collaboration meetings in Europe (each $5k per year approx.) For the Adelaide group these costs apply to only one person (Rowell). Funding for Adelaide's membership of HESS-II continues to rely on ARC (Discovery) and University programmes. The demise of the ANSTO-managed AMRFP funding programme in 2011 has reduced opportunities to secure long-term funding for basic operational costs such as observation shift operations.

A consortium of six Australian universities joined CTA as an associated party in 2013. Full membership (to bring benefits outlined in §3.3) requires parties to contribute construction costs. The fraction of these costs and operational costs assigned to each country are still be finalised, but it is necessary that Australia commences efforts to raise these contributions as soon as possible. Over the next few years, construction and then operational costs will be sought from ARC LIEF programmes (at the level of approx. $500k per proposal) and institutional funds. The level of staff and student involvement in observational aspects of this field is expected to rapidly increase as CTA builds up. The six Australian institutions (representing 10 or more tenured staff) already involved in the ARC-LIEF bid for CTA support testify to a solid foundation of interest.

We consider access to non-ARC block funding such as NCRIS, EIF and Super Science schemes as critical to ensure long-term stability of Australian access to these facilities, to avoid uncertainties associated with ARC programmes. Of particular importance is the need to relax the rules of inclusion regarding each round of NCRIS et al. type funding to ensure a level of sta-

[18] http://dpnc.unige.ch/dampe

[19] http://calet.phys.lsu.edu

[20] http://gamma400.lebedev.ru/indexeng.html

ble funding can be applied across a broad spectrum of Australian astronomical activities. As an example, one suggestion could be to ensure a small (5 to 10%?) fraction of any new NCRIS-type funds can be allocated to projects not previously funded under such schemes. Finally, re-instating a facilities access scheme such as AMRFP or ARC Small Grants would also be most welcome.

References

[1] Giebels B., H. E. S. S. Collaboration 2013, arXiv:1303.2850

[2] Abdo A.A. et al. 2007 Astrophys. J. 664, L91

[3] Abdo A.A. et al. 2009 Astrophys. J. 706 L138

[4] Abramowski A., et al. 2012 Astron. & Astrophys. 548, A46

[5] Aharonian F.A., et al. 2006 Astron. & Astrophys. 460, 365

[6] Aharonian F.A. et al. 2008 Astron. & Astrophys. 481, 40

[7] Berström L. et al. 2012 J. Cosmol. Astropart. Phys. 11, 25

[8] Burton M. et al. 2013 ISM White Paper arXiv:1307.0712

[9] CTA Science - Special edition of Astroparticle Physics 2013, 43, 1-356

[10] Hilla A.M. 2013 Astroparticle Physics 43, 19

[11] de Naurois M. et al. (HESS Collab.) 2013, Advances in Space Research, 51, 258

[12] Nicholas B. et al 2012 MNRAS 419, 251

[13] Petrov L. et al. 2013 MNRAS 432, 1294

[14] Rieger F. et al. 2013, Frontiers of Physics, 8, 714

[15] Su M. et al. 2010, Astrophysical Journal, 724, 1044

[16] Tanaka S., & Takahara F. 2010 ApJ 715, 1248

[17] Yamazaki R. et al. 2006 MNRAS 371, 1975

4 COSMIC RAYS AND NEUTRINOS

Cosmic ray and neutrino astrophysics is primarily concerned with discovering the nature and acceleration sites of high energy ($\geq 10^{15}$ to 10^{20} eV) cosmic rays. Since gamma-rays and neutrinos can be by-products of cosmic ray acceleration, these areas have a high degree of synergy with gamma-ray astrophysics (see §3). Furthermore, the techniques used by ground-based current and future insturments such as the Pierre Auger Observatory, HESS, IceCube and CTA have many commonalities.

Along with ground-based VHE gamma-ray observations, cosmic ray astrophysics was identified as a “New and Emerging Research Area” in the mid-term review of the previous decadal plan. Australia has long played a leading role in the 600-strong international collaboration that operates the Pierre Auger Observatory[21], studying the nature and origin of the most energetic particles known in the Universe.

In recent years, a national research profile in neutrino astrophysics has emerged, with U. Adelaide links to the IceCube[22] neutrino observatory at the South Pole. IceCube is the world's largest neutrino detector, comprising about 5000 optical modules deployed within a cubic kilometer of ice. Unlike cosmic rays, neutrinos travel in straight lines, their arrival directions pointing back to the source origin – albeit with a positional error based on the type of secondary particle seen (muon - less than 1 degree, or cascade - of order 10 degrees). Nonetheless, the neutrino skymap is a map of the sources of these particles, and, if models of particle acceleration and production in energetic objects are correct, these sources are likely to be sites of cosmic ray acceleration. IceCube is designed to detect neutrinos arising from the most violent astrophysical sources: supernovae, gamma ray bursts, and cataclysmic phenomena involving black holes and neutron stars. Dark matter is also a priority for the instrument, and there is substantial overlap with the dark matter detection experiments (see §6). Since 2004, the Lunar Ultra-high-energy Neutrino Astrophysics using SKA[23] (LUNASKA) project has sought to detect Cerenkov radiation arising from the interaction of UHE neutrinos with lunar regolith.

4.1 Progress against objectives

The 2011 Mid-Term Review of the previous decadal plan outlined the growth of Australia's involvement in ground-based high energy astrophysics through investment in new observatories such as Auger, HESS, and LUNASKA. This work is built on Australia's excellent long-term record of achievement in the study of very-high energy cosmic rays, and is characterized by a strong international dimension.

Pierre Auger Observatory Australia's involvement in the Auger collaboration is currently via the University of Adelaide group, with 4 senior scientists and eight PhD students. In full operation since 2008, the 3000 square kilometre facility in western Argentina remains the leading international cosmic-ray facility. During the past five years, the Auger Collaboration has made a number of major breakthroughs in the field, all with strong Australian involvement. First, a suppression of the cosmic ray flux at energies above 5.5×10^{19} eV has been established unambiguously (2; 3). Second, due to the Auger limits on photon and neutrino fluxes at ultra-high energy, it is now clear that unusual "top down" source scenarios, such as the decay of super-heavy primordial particles, cannot account for a significant part of the observed flux (4; 5). Third, there are indications of an anisotropic distribution of the arrival directions of particles with energies greater than 5.5×10^{19} eV (6; 7), with an apparent correlation with the directions of nearby active galaxies. Finally, and contrary to most expectations, Auger has identified a dom-

[21] http://www.auger.org

[22] http://icecube.wisc.edu

[23] http://www.physics.adelaide.edu.au/astrophysics/lunaska

inant heavy component of the mass composition of cosmic rays at the highest energies, based on Auger's air shower measurements and the best understanding of hadronic physics interactions at particle energies well above those probed at the Large Hadron Collider. Protons are likely to be a sub-dominant component compared with middle-mass nuclei (CNO) and even iron (8; 9). Overall, many source scenarios have been ruled out, and the nature of the flux is now better understood allowing for even more fruitful source searches in the near future.

IceCube Observatory The ambitious neutrino detector was completed in late 2010, and now fully operational for three years, it has already produced a major discovery – a flux of diffuse high-energy neutrinos coming from beyond the Earth's atmosphere (11). The University of Adelaide became a member of the collaboration in late 2011, and has played a leading role in the analysis of these data, and is working to improve the methods used to identify and characterise the diffuse neutrino flux. The Adelaide IceCube group currently includes two senior physicists and three graduate students. To date, more than 30 high-energy extra-terrestrial neutrinos have been identified. Work is underway to improve the pointing and energy reconstruction of IceCube, to better localise the sources, and to interpret the existing data, for instance by searching for classes of objects that might correlate with the neutrino detection locations.

Neutrino astrophysics has also been pursued via large-scale cosmological simulations, WiggleZ galaxy survey data, in combination with observations from the Planck satellite (1).

4.2 Stocktake of capabilities/resources

Cosmic Rays The Pierre Auger Observatory in Argentina is currently the experiment with the greatest sensitivity in the study of UHE cosmic rays, having a collecting area exceeding 3000 square kilometres. A factor of four smaller, the US/Japan Telescope Array Observatory[24] in Utah studies the northern skies with some overlap with Auger's view of the south.

Both Auger and the Telescope Array are planning upgrades in the next 5 years, with Auger maintaining a significant lead in overall sensitivity. Auger will install new detectors within the existing 3000 square kilometre area to augment its ability to determine the likely mass (and hence charge) of each incoming cosmic ray. This is a consequence of Auger's discovery of a significant high-mass component of the cosmic ray flux at the highest energies; improved identification of the proton cosmic rays, with their single charge and minimal deflection in cosmic magnetic fields, will greatly improve source search sensitivity. Details of the $\sim$US$12M upgrade project are being finalized by the collaboration in 2014, but the essence of the proposal is that the new detectors will measure the muon component of the cosmic ray air showers, and electronics enhancements to the existing surface detectors will improve measurements of the development characteristics of each air shower, both fingerprints of the mass of the initiating

[24] http://www.telescopearray.org

cosmic ray.

Longer term, plans are progressing for a new world-wide collaboration, including both the Auger and Telescope Array collaborations, to construct a ground based observatory with an area of 20,000 square kilometres. In parallel, other techniques are being studied in earnest, the most advanced being the pioneering space-based JEM-EUSO project planned for the Japanese Experiment Module on the International Space Station. In addition, Australian radio and cosmic ray astronomers with the LUNASKA project are exploring the capabilities of the Square Kilometre Array for viewing cosmic ray and neutrino interactions in the moon. In principle this technique offers excellent detection sensitivity at the very highest energies. The detection technique will be validated with SKA Phase 1, but the full promise cannot be tested until SKA Phase 2, beyond the scope of the current decadal plan.

It is expected that the best way forward will be clear beyond 2020, when sufficient data from the Auger upgrade are available. If a significant heavy component of the UHE flux is confirmed, ground based solutions may be favoured over space-based and lunar solutions because of their superior mass composition and energy resolution. It is not expected that significant funding will be sought for this next generation observatory within the current decadal plan period.

Astrophysical Neutrinos The lifetime of the IceCube instrument is expected to be at least 10-15 years, extending well into the next decade. Driven by the recent discovery of a diffuse flux of neutrinos coming from beyond the Earth's atmosphere, much effort is in progress aimed at upgrading IceCube in some form to increase its senstivity to neutrinos with energies of 1 PeV and beyond, especially for the new downward going contained event selection channel, the cornerstone of the diffuse flux discovery analysis. Potential upgrades include deploying more IceCube-like detector strings to expand the detection volume, and deploying surface detectors, both particle and optical, to detect and veto downward moving atmospheric airshowers, enhancing the detection senstivity of the in-ice array to contained downward moving astrophysical neutrinos.

At the very highest energies, where cosmic rays are attenuated on the cosmic microwave background (the Greisen–Zatsepin–Kuzmin or GZK effect), we expect a flux of neutrinos, and construction and planning for the Askaryan Radio Array[25] (ARA) is underway. This instrument is designed to detect coherent Cherenkov radiation from the interaction of the GZK neutrinos with the ice. The planned detector would cover an initial 80 square kilometres of the ice with about 40 stations, each consisting of radio receivers deployed to more than 100 metres into the ice.

[25] http://ara.physics.wisc.edu

4.3 New opportunities/requirements

Cosmic-ray research in Australia is continuing to evolve, with an Auger upgrade to begin in 2015, and Australia joining two other large international collaborations – the existing IceCube neutrino observatory at the South Pole, and the planned Cherenkov Telescope Array (CTA) TeV-gamma-ray observatory (see §3.3). There is enormous synergy in these ground-based high energy astrophysics pursuits.

In cosmic rays, the Australian effort in the next five years will concentrate on the implementation of the upgrade of the Pierre Auger Observatory, with its three primary goals — first, to identify the origin of the cosmic ray flux suppression at the highest energies (exhaustion of the accelerators, or energy-loss interactions of cosmic rays with the microwave background radiation?); secondly, to carry out enhanced source searches based on event-by-event estimates of the cosmic ray mass; and thirdly to investigate hadronic interaction physics at centre-of-mass energies near and beyond 60 TeV, well beyond energies accessible at the Large Hadron Collider. In parallel, Australia will contribute to studies of future cosmic ray observatories comparing the capabilities of ground-based detection, space-based observatories and the detection of lunar interactions using the SKA. The next-generation of cosmic ray observatory will likely be calling for support in the last few years of the upcoming decade.

Australian theorists are already contributing to our understanding of the possible sources of ultra-high energy cosmic rays and neutrinos, for example in relation to acceleration sites that may be associated with the supermassive black holes and relativistic jets of active galaxies. As the cosmic ray and neutrino observational data matures more in the next decade, there will be even more need for theoretical input to our understanding of the astrophysics.

Our greater understanding of the high energy data will also allow for more fruitful engagement with the broader Australian astronomical community, especially in radio studies of possible cosmic ray acceleration sites within our Galaxy and beyond. Studies of intergalactic and galactic cosmic magnetism using Faraday tomography techniques will inform cosmic ray studies, and conversely, discoveries of sources of cosmic rays will provide data on magnetic fields between the source and Earth.

As more detailed large-scale galaxy structure surveys and new Planck data are released, there is also the opportunity to make major new advances in the study of neutrinos from cosmological data.

4.4 Suggested strategies and resourcing levels

Australia has maintained a leading role in understanding the origin of the highest energy cosmic rays through relatively modest monetary contributions to the international Pierre Auger Collaboration (typically $150K p.a.). That investment has leveraged access to the leading experiment in the field and significant benefit to Australian researchers and students. This model now has been extended to membership of the IceCube Collaboration with its equally rich science facilities now available to Australian researchers.

Continued activity in the Pierre Auger Collaboration will require contributions of approximately $200K of hardware costs towards the US$12M upgrade in the period 2015–17. Funds will be sought through ARC competitive funding schemes.

Pierre Auger Observatory subscription costs of $30–40K p.a. are envisaged for the next decade. A similar amount will be required for annual Australian membership of the IceCube collaboration. Echoing the previous Mid-Term Review, strong consideration should be given to sourcing these observatory subscription fees from a future NCRIS-type funding stream. This would provide a great deal of stability to Australia's involvement in Auger and IceCube in the face of the uncertainty of the competitive funding schemes.

Australia's expertise in remote site Antarctic Astronomy, and high-energy neutrino astrophysics makes the ARA an attractive prospect for Australian involvement. Plans exist to fund such involvement through competitive grant schemes, such as ARC Discovery and LIEF programs. To make a meaningful contribution, funding would be needed at least at the level that would ensure the participation of a postdoctoral researcher and PhD students.

We would suggest that any successor to the Super Science scheme for astronomy be broadened to include funding for bright young postdoctoral researchers in all area of astrophysics, including observational and theoretical researchers in ground-based high-energy astrophysics.

References

[1] Riemer-sorensen, S. et al. (2014) Phys. Rev. D 89(10), #103505

[2] Pierre Auger Collab., J. Abraham et al. (2008) Phys. Rev. Lett. 101, 061101

[3] Pierre Auger Collab., J. Abraham et al. (2010) Phys. Lett. B685, 239

[4] Pierre Auger Collab., J. Abraham et al., (2009) Astropart. Phys. 31, 399

[5] Pierre Auger Collab., P. Abreu et al. (2011) Phys. Rev. D84, 122005

[6] Pierre Auger Collab., J. Abraham et al. (2007) Science 318, 938

[7] Pierre Auger Collab., P. Abreu et al., (2010) Astropart. Phys. 34, 314

[8] Pierre Auger Collab., J. Abraham et al. (2010) Phys. Rev. Lett. 104, 091101

[9] Pierre Auger Collab., P. Abreu et al. (2013) JCAP 1302, 026

[10] Pierre Auger Collab., P. Abreu et al., Astropart. Phys. 34, 627 (2011).

[11] M. Aartsen et al., (IceCube collaboration) Science 342 1242856 (2013)

5 NUCLEAR ASTROPHYSICS

The primary focus of nuclear astrophysics is tightly related to processes in stars and stellar evolution. The previous decadal plan in 2006 included the key question "How do stars produce and recycle the elemental building-blocks of life?" This question remains open, and stellar nucleosynthesis is a active, high-priority international research field. Another source of nucleosynthesis is due to cosmic rays (§4). Finally, there is also nucleosynthesis in the big bang (1) (BBN), which is relevant in a cosmological context, as BBN is a sensitive probe to some of the cosmological parameters, e.g., the cosmological mass density of baryons. The next steps in our understanding of galaxies and galaxy clusters requires to include nucleosynthesis - feedback from stars and supernovae, neutron stars and black holes. Thus, nuclear astrophysics in general has large overlap with WG 1.2 (stars and planets), as well as WG 1.1 (galaxies and cosmology). The discussion in this section focuses on explosive stellar nucleosynthesis, including supernovae, and on nuclear physics in neutron stars, which is not part of the discussions in WG 1.2.

5.1 Progress against objectives

Nuclear astrophysics in Australia was at a nascent stage at the time of the previous decadal plan. Even in the 2011 mid-term review, the word "nuclear," or its derivations, did not appear a single time. The *first stars* were mentioned in the context of the epoch of reionisation in connection with the Square Kilometre Array[26] (SKA). Despite this, we have come a long way in the last decade, and Australia has arguably emerged to dominate this field, led primarily by the observational group at the Australian National University (ANU). Notable results include the discovery of the most iron-poor star known (3) almost a decade ago; this record-holder has only recently been supplanted by an even more iron-poor star, also discovered by Australian astronomers (4). An additional focus on explosive nucleosynthesis in supernovae and neutron stars is now represented by observers and theorists at ANU, Monash, and Swinbourne.

Australia has taken one of world's leading roles in studying stellar evolution and nucleosynthesis, from low-mass stars, where it is world-leading, and extending to massive stars and supernovae. A particular focus of Australian researchers has been on the first stars and their nucleosynthesis. Better understanding of stellar nucleosynthesis has also come from studies of pre-solar gains that uncover abundance pattern directly form inside stars, and that we are now trying to understand based on simulations. Binary stars and numerical simulations of galacto-chemical evolution has arguably not reached a critical mass, though there are some of the best observational experts and efforts in place. Dual drivers for these developments have been instrumental improvements, in addition to improved atmosphere models. Some of the nucleosynthesis processes, e.g., r-process, do remain elusive, however.

5.2 Stocktake of capabilities/resources

Over the last decade, Australia has become one of the more prominent places world-wide for nuclear astrophysics. Much of this growth has been driven by world-class observers and ob-

[26] `https://www.skatelescope.org`

servational facilities (e.g., SkyMapper[27], and HERMES, via the GALAH[28] survey). Australia is also home of probably the largest collection of researchers who study nucleosynthesis in low-mass stars including asymptotic giant branch (AGB) stars, and s-process. Especially with supernova observation, but also from the side of theory, this is now starting some world-class research in massive stars, supernovae, and their nucleosynthesis (massive star and SN nucleosynthesis, core collapse supernovae, gamma-ray bursts). Australia now has also built up expertise in modelling of core collapse supernova, including multi-dimensional simulations that include neutrino transport and general relativity (Monash; 5). These simulations, hence, not only provide results for nucleosynthesis and light curves that can be observed throughout the electromagnetic spectrum, but also gravitational wave and neutrino signals. This constitutes a true multi-messenger capabilities to study the deaths of massive stars and the formation of neutron stars and black holes.

In the last 10 yr, there has also been significant build up in neutron-star physics and observations in Australia, ranging from the theory of dense nuclear matter inside neutron stars, to numerical modelling of neutron star and thermonuclear processes in their interior and on their surface, to world-leading observations of neutron stars and pulsars, from radio to X-rays.

The experimental side of nuclear astrophysics is more limited as Australia does not have large-scale national accelerator facilities for nuclear research or nuclear research reactors. Nationally, nuclear physics research is concentrated at ANU, where the Department of Nuclear Physics consists of 3 groups: nuclear structure (Stuchbery, Kibedy, Lane, Dracoulis), nuclear reaction dynamics (Hinde, Dasgupta, Simenel) and Accelerator Mass Spectroscopy[29] (AMS; Wallner, Tims, Fifield). The department runs the Heavy Ion Accelerator Facility (HIAF[30]); the only such facility in Australia for nuclear physics studies. It is unique in the sense that it provides among the highest particle energies available for AMS, which is a key feature for some applications.

The ANU group carries out AMS to study pre-solar grains, which makes Australia competitive on an international scale in this field. Secondary ion mass spectrometry is used to measure isotopes in these grains, with the objective of testing models of stellar evolution, nuclear reactions, and galactic chemical evolution. These efforts are in collaboration with astrophysicists at ANU and Monash. In the last few years, they have concentrated their work on measurements of heavy elements on grains formed in C-rich AGB stars. The presolar data provides high-precision constraints on AGB nucleosynthesis and reaction rates critical to s-process nucleosynthesis; time of residence of presolar grains in the ISM; and galactic chemical evolution (2). They have also been working on "cosmochronology" – the determination of absolute ages of presolar grains and their parent stars . This has long been a priority for the research area, but

[27] http://rsaa.anu.edu.au/observatories/telescopes/skymapper-telescope
[28] http://www.mso.anu.edu.au/galah/home.html
[29] http://physics.anu.edu.au/nuclear/research/ams
[30] http://physics.anu.edu.au/nuclear/hiaf.php

the analytical capabilities to date have been insufficient. The ANU group were able to measure the abundance of key isotopes like ^{238}U and ^{232}Th in presolar grains with their instruments.

AMS is used in a much wider range of applications; the best known of course is radiocarbon dating. Until recently, the experimental focus at ANU was on environmental and geological applications, climate and soil/erosion studies, and meteorites etc. Presently, a strong focus on nuclear astrophysics and nuclear physics applications to astrophysics has emerged. In general, the AMS facility at the ANU provides for some measurements the highest sensitvity world-wide, thus making it a powerful tool for measuring some specific long-lived radionuclides.

5.3 New opportunities/requirements

There is much scope for further exploitation of the AMS facility at ANU for use in nuclear astrophysics.

Most experimental nuclear astrophysics, however, must instead rely on collaborations with teams on new experimental facilities in Europe, including GSI's Facility for Antiproton and Ion Research[31] (FAIR, currently under construction) and in the US (FRIB[32]) where more n-rich and p-rich nuclei will be studied than currently accessible. There are similar facilities available at RIKEN in Japan, as well as experiments at CERN, and capabilities that are being developed in China, e.g., a facility similar to FAIR at Lanzhou[33], and the JUNA underground laboratory (currently in proposal stage to a specific call). A promising opportunity for nuclear astrophysics in the US is the next iteration of the Joint Institute for Nuclear Astrophysics (JINA[34]), the Centre for the Evolution of the Elements (JINA-CEE), recently awarded funding by the National Science Foundation (NSF; Frontier Center) at a level of more than US$2.2M/yr for 5 yr. Several groups in Australia are already associated with this centre.

China is now putting significant investment into basic research to increase the visibility of its major universities, which also includes the foundation of centres for nuclear astrophysics (e.g., at Shangai Jiao Tong University[35]). There are significant opportunities for Australia to get involved, particularly with Chinese universities keen to form strategic alliances with Australian universities. These partnerships will benefit both parties, trading personnel and expertise for access to new and well-funded research facilities, as well as exchange of students and senior researchers.

Goals for nuclear physics modeling include full-scale core collapse supernova simulation with full neutrino transport and including general relativity. Currently the computational resources in Australia may not be sufficient to enable progress in this area; full 3D simulations with full neutrino transport will require machines on the exa-scale, similar to supercomputing

[31] http://www.fair-center.eu
[32] http://www.frib.msu.edu
[33] http://english.imp.cas.cn
[34] http://www.jinaweb.org
[35] http://en.sjtu.edu.cn

investments for SKA but general-purpose machines. If the Australian resources are not built up accordingly, Australian researchers will need to sign up as "junior partners" with international collaboration in order to have any chance for participating in current forefront research. For being leader in the field, Australian national resources are required.

In terms of astronomical instrumentation, Australia has a world-leading position in stellar spectroscopic surveys. Access to 8m-class telescopes must also be maintained for followup high-resolution spectroscopy of key sources. This access is a high priority for other groups, and nuclear astrophysics can expect to piggyback off national-level partnerships, and/or direct access based on financial contributions, if not as collaborators on smaller international research collaborations.

The future of studying stellar deaths is multi-messenger observations. This includes gravitation wave detection and neutrino signal from supernova, and gravitational waves from binary neutron star mergers, one of the most promising sites for nucleosynthesis by the r-process. These have to be combined with both rapid follow-up multi-wavelength observations as well as deep observations with large telescopes and spectroscopic capabilities. Only this way can we well leverage existing Australian capabilities and expertise. Both capabilities are are currently not present or very limited (e.g., IceCube[36] for the highest-energy neutrinos). International agreements for stronger participation of Australian researchers and institutions in such projects need to be reached; in the long run, buildup of such capabilities in Australia should be considered.

Expertise in nuclear theory will become increasingly more important to keep up with nuclear experimental data on the international scale and to provide the input for state of the art nuclear astrophysics. In fact, astronomical observations can provide significant constraints on nuclear theory, e.g., the recent discoveries of neutron stars with masses of about 2 solar masses (6) help us to constrain the nuclear equation of state, and thus help us to better understand the properties of atomic nuclei.

For AMS one of the main problems in Australia is the shortage of personnel working with presolar grains (and planetary sciences in general). It is not clear whether this is due to the lack of funding, lack of interest from young researchers/students, or whether we need a better strategic plan to attract meteoritic researchers to Australia. The ANU group is pursuing several approaches to improve the situation, incorporating collaborative studies into nuclear reactions of relevance to s- and p process; searches for isotopic fingerprints of supernovae and the interstellar medium in terrestrial samples; and long-lived radionuclides in meteorites.

5.4 Suggested strategies and resourcing levels

Australia will likely not be in the position to develop new experimental nuclear, neutrino, or gravitational wave facilities on international competitive level on its own; most data will be

[36] `http://icecube.wisc.edu/`

in form of international collaborations. A key strategy for the future is thus maintaining and growing international collaborations with US, China, Europe, and Japan.

The modest level of experimental development at ANU represents an important part of local research efforts, but likely also a critical element of any future development, and thus the experimental facilities there should be maintained. Involvement in IceCube will give us access to some form of neutrino telescope, though its use for common supernovae is limited.

In the area of pre-solar grains, in which Australia has gained a solid reputation, we can still have some international impact with a modest investment.

Australia has secured a unique leading role in surveys including spectroscopy that constitute the science on observational nuclear astrophysics of the next decade. Australia needs, however, to secure observation time on large telescopes with high-resolution spectrographs to maximize the impact of current investment.

Australia has collected comprising and world-leading expertise in theoretical nuclear astrophysics covering the full range from low-mass stars, massive stars, supernovae, and neutron stars, and the nuclear processes in them. This needs to be complemented with nuclear theory relevant to nuclear astrophysics.

Much of the next decade will be in the domain of multi-dimensional simulations and large-scale data sets. We need to secure supercomputing facilities that match international standards to continue to do competitive science, and we will also need the manpower to develop the codes and run the numerical simulations.

References

[1] Boesgaard, A. M. & Steigman, G. (1985), ARAA 23, 319

[2] Lugaro, M. et al. (2014), Science 345, 650

[3] Frebel, A. et al. (2005), Nature 434, 871

[4] Keller, S. et al. (2014), Nature 506, 436

[5] Müller, B, & Janka, H.-T. (2014), ApJ 788, 82

[6] Demorest, P. B., et al. (2010), Nature 467, 1081

6 DARK MATTER

The existence of dark matter is the most concrete evidence that new particles exist. Following the recent discovery of the Higgs boson, the final element of the particle physics standard model to be confirmed experimentally, it is clear that identification of a dark matter particle is now the leading priority. However, at present, direct detection results are confusing, with the signals detected in some experiments (e.g. DAMA[37], CoGeNT[38], CRESST[39]) in conflict with null-results from others (e.g., LUX[40], XENON[41]).

The most likely dark matter candidates are weakly interacting massive particles (WIMPS), massive particles with GeV–TeV scale masses, and interaction strength similar to that of the weak interactions. They arise in supersymmetry and many other well motivated particle physics models. WIMPS would have been thermally populated in the early universe. Importantly, they have the correct mass and interaction strength to account for the relic abundance of dark matter in the universe today - a fact known as the "WIMP miracle". Moreover, the mass and interaction parameters suggested by the WIMP miracle can be tested experimentally, with direct detection experiments, indirect detection searches, and collider searches providing important complementary information.

The study of dark matter is generally approached via direct detection experiments, or experiments which infer properties via studies of large-scale structure and evolution. While minimal Australian involvement has occurred in the former area, the latter has been extremely active, benfiting from complementary studies of galactic structure and evolution. Observational and simulation studies of galactic evolution are of high priority to working group 1.1, Galaxies and Cosmology.

6.1 Progress against objectives

The previous decadal plan addressed dark matter in two specific contexts: galaxy formation (i.e., dark matter halo formation) studies; and investigations of the Tully-Fisher law. We have made significant progress in both these areas.

In the area of galaxy formation (from the perspective of the build-up of dark matter halos), much of the progress has been driven by major numerical simulation efforts, such as the Survey Simulation PipeLine (SSimPL) Gigaparsec WiggleZ[42] simulations (GiggleZ), and Dark-ages Reionization and Galaxy Formation Simulation (DRAGONS) projects, which are large-scale cosmological simulations based on *n*-body codes, which produce halo merger trees and mock galaxy catalogs.

Our studies of the Tully-Fisher law (or, specifically, of the evolution of galaxy rotations and masses over cosmic time) have made huge leaps since the development of the 2MASS Tully-Fisher (2MTF[43]) survey (in which Australia has a strong involvement) and the SAMI[44] survey, which uses a multi-object integral-field spectrograph to observe the rotation of galaxies with

[37] http://people.roma2.infn.it/~dama
[38] http://cogent.pnnl.gov
[39] http://www.cresst.de
[40] http://lux.brown.edu
[41] http://xenon.astro.columbia.edu
[42] http://wigglez.swin.edu.au
[43] http://ict.icrar.org/2MTF
[44] http://sami-survey.org

Doppler measurements across wide regions. While the study of dark matter in particular is not officially a key part of SAMI's science case, it will form a major contribution to our understanding of the build-up of angular momentum in galaxies. Even more relevant to dark matter is the fact that the Tully-Fisher relation is crucial for measuring the distances to spiral galaxies, allowing us to better measure peculiar velocities and trace gravitational potentials on large scales. This is another area not mentioned in the previous decadal plan, but which is emerging as a strength of the astronomical community in Australia.

6.2 Stocktake of capabilities/resources

Current strengths in the area of dark matter studies are wide-ranging. As discussed above, major simulation efforts have provided new dark matter halo merger trees and (simulated) galaxy catalogs. These simulations include GiggleZ, SSimPL and DRAGONS. The relationship between the shape of dark matter halos and feedback mechanisms and galaxy growth is being investigated through simulations combining dark matter and hydrodynamics (1). This work is currently being followed up in the context of the DRAGONS simulation. Recent studies (2, see e.g.) have shown that baryonic process can affect the shapes of dark matter density profiles in galaxies, which has significant consequences for the so-called "cusp-core problem." Other small-scale anomalies in the cold dark matter paradigm may also be solved through a more complete treatment of dark matter / baryon interactions, such as the missing-satellite problem (3) and the "too big to fail" problem (4). Simulations of warm dark matter and dark matter halo inner profiles are also being developed to address a range of problems in the cold dark matter paradigm, including the satellite problem and the cusp-core problem (see, e.g. 5; 6, and other work led by Power and collaborators).

The SAMI instrument has allowed us to carry out new and innovative work in the study of galaxy rotation (7). The final survey will allow us to get 2D spectroscopy on tens of thousands of galaxies, and will be a powerful tool in the study of dark matter in galaxies. Resolved rotation data from the SAMI instrument has been used in an innovative program led by researchers at U. Melbourne to measure the gravitational shear in individual galaxies, which could give us invaluable insight into dark matter halos. This technique, called direct shear mapping, is still under development, but appears to be a promising new tool.

Australian astronomers have long been leaders in cosmological microlensing, which can be used to study the mass function of objects in lensing galaxies and place constraints on dark matter content (8).

Peculiar velocity studies are enabling us to directly map out the distribution of dark matter and to measure large-scale bulk flows (and therefore gravitational potentials) in the Universe. Leading projects in this area are the 6dFGSv survey (a development of the 6dFGS[45] survey)

[45] http://oldweb.aao.gov.au/local/www/6df

2MTF (mentioned above) and the WALLABY[46] survey of HI with ASKAP (when paired with the Westerbork Northern Sky HI survey, WNSHS[47]).

6.3 New opportunities/requirements

While we are making significant progress in many of these areas, we have the opportunity to more fully develop this work and build upon our existing strengths. The three areas of most promise are: SAMI and galaxy redshift surveys; the Theoretical Astrophysics Observatory (TAO[48]); gravitational microlensing and shear mapping; and simulation programs.

The SAMI instrument puts Australia in a position to be a world leader in studies of galaxy rotation, and we should continue our focus on this. Similarly, we can use our expertise in galaxy redshift surveys and our access to data from WiggleZ to build upon what is already a major role in the mapping of dark matter in the Universe on large scales.

We have several innovative simulation programs underway that are making major advances in our study of the physics of dark matter and galaxy formation. These developments will also feed into the TAO, and potentially boost the impact of the simulation efforts. While TAO is still under development, it is highly promising as a tool for the interpretation of observational survey data and for predictions with alternative cosmologies.

We have made major advances in the use of gravitational lensing (in the form of cosmological microlensing and, should it pan out, direct shear mapping) as a tool for the study of dark matter. This area should receive more emphasis than it currently does, given our high level of expertise even with the fairly limited investments already made.

Finally, there is growing interest in a dark matter experiment in Australia, with a gold mine in Stawell identified as a possible location. The confliciting results of current direct detection experiments in the northern hemisphere may be resolved via complementary measurements from a southern hemisphere experiment, especially regarding annual modulation signals.

6.4 Suggested strategies and resourcing levels

As cosmological data becomes ever more precise, we have new opportunities to tackle fundamental physics problems in cosmology. These include the nature of dark matter, early universe physics, fundamental particle physics, and the nature of dark energy. In the area of dark matter physics in particular, advancements in particle physics (such as in colliders and direct detection experiments) inform the dark matter models whose indirect effects are investigated in cosmology, and cosmological constraints inform particle physics experimental designs. Following the example of the gamma-ray and cosmic-ray astrophysics communities, we should encourage the continuing development of astro-particle physics. Increasing links, through joint

[46] http://www.atnf.csiro.au/research/WALLABY

[47] http://www.astron.nl/~jozsa/wnshs

[48] https://tao.asvo.org.au

initiatives, connections between centers, investments in cross-disciplinary projects, and dedicated meetings (or meeting sessions) and workshops have the potential for high-impact payoffs. A new center of excellence for astroparticle physics would likely be especially productive. This would also allow us to better exploit our existing expertise, including the advances being made in the Australian particle physics community, which has heavy involvement in the Large Hadron Collider.

Australia is currently investing in the Cherenkov Telescope Array (see Section 3.3), which will be sensitive to dark matter annihilation signatures from the Galactic Center and dwarf galaxies as well as possible signatures from axion dark matter's effects on the extragalactic gamma-ray background (9). These are important signatures in indirect dark matter detection. Hints of possible indirect dark matter signatures have also been seen recently in x-ray observations of galaxy clusters (10), suggesting another area where future and existing efforts in observational astronomy could be fruitful for the dark matter search (see Section 11.3.4).

Further development of new surveys including 6dFGRSv, 2MTF and WALLABY are worthwhile investments in the future. The simulation programs will require sufficient computing resources to build on past successes and allow us to make new advances in this area. Further development of the TAO and promoting its use in the community, will complement continued investments on the observational side.

References

[1] Duffy, A. R. et al. (2010), MNRAS, 405, 2161
[2] Pontzen, A. & Governato, F. (2012), MNRAS 421, 3436
[3] Brooks, A. et al. (2013), ApJ 765, 22
[4] Brooks, A. & Zolotov, A. (2014), ApJ 786, 87
[5] Power, C. et al. (2003), MNRAS 338, 14
[6] Knebe, A. et al. (2008), MNRAS 386, 1029
[7] Croom, S. M. et al. (2012) MNRAS 421, 872
[8] Bate, N. F. et al. (2011), ApJ 731, #71
[9] Doro, M. et al. (2013), Astroparticle Physics 43, 189
[10] Bulbul, E. (2014), ApJ 789, 13

7 PULSARS

The last decadal plan explained that pulsars could be used to answer some fundamental questions about the nature of gravity:

> Is our understanding of gravity correct? Nature's most accurate clocks are pulsars — the rapidly rotating collapsed remnants of massive stars. Pulsars have enor-

mously strong gravitational fields, and provide a unique laboratory for testing theories of gravity under conditions that are impossible to probe in Earth-based laboratories. Nobel prizes for Physics in 1974 and 1993 underline the importance of pulsars as a link between fundamental physics and astronomy. Some of the most stringent tests of gravitational theories will come from research into pairs of pulsars that orbit each other, and especially from as-yet undiscovered binary systems in which a pulsar orbits a black hole. These systems are rare but provide crucial tests of general relativity and the fundamental nature of gravity.

As acknowledged in the mid-term review, a complementary effort has emerged with the goal of using assemblies of well-timed pulsars to search for very low-frequency (nHz) gravitational waves. This effort commenced with the Parkes Pulsar Timing Array (PPTA; 1) and has since expanded internationally to include, at present, three closely-linked efforts.

7.1 Progress against objectives

Progress in this area has been dramatic. Surveys at the Parkes 64m radio telescope have continued to discover large numbers of millisecond pulsars crucial for tests of general relativity. The High Time Resolution Universe (HTRU[49]) surveys for pulsars and fast transients has discovered over 25 new millisecond pulsars (2). The celebrated double pulsar discovered at Parkes led to the most accurate confirmation of the theory of General Relativity (5). Another white dwarf pulsar binary was exploited to verify that in dissymmetric binaries gravitational wave emission is consistent with GR (6). The binary pulsar PSR J1738+0333 has been used to make the most stringent tests of scalar-tensor theories of gravity (7). The bright millisecond pulsar PSR J0437-4715 has been used to limit the time derivative of G (9). A pulsar black hole binary remains elusive.

Although not a stated objective of the previous plan, the last decade has also seen growing interaction between pulsar astronomers and the gravitational-wave community, and extensive development of pulsar timing arrays (PTAs). Millisecond pulsars discovered in the HTRU and other surveys are being incorporated into the Parkes PTA (PPTA) and hence into the International Pulsar Timing Array (IPTA; see e.g. 3), a consortium of the three large international PTA projects. The world-leading PPTA data set has recently been analysed to yield the most stringent upper limit on the strength of the nHz gravitational-wave background (4). This limit eliminates some proposed models for the formation and evolution of super-massive black holes in the early Universe. In the high-frequency regime, the ephemerides of known pulsars have been used to limit their gravitational wave emission using data from the science runs of initial-LIGO (8).

Australia's geographical location and excellent radio instrumentation make it a world leader in observations of radio pulsars, as they are a predominantly Southern population. Over the

[49] http://astronomy.swin.edu.au/pulsar/?topic=hlsurvey

years this has led to a natural relationship between observers and theorists, with strong groups at the University of Sydney under Melrose and more recently at the University of Melbourne with the establishment of Melatos' group. The polarimetry, single pulse energetics and relation to X- and gamma-ray profiles provide an opportunity to probe fundamental physics in conditions impossible in the laboratory. With regard to gravitational wave emission, theorists are providing new opportunities for gravitational wave detection and limits via predictions that can be tested using observations with both Parkes and gravitational wave observatories like LIGO.

7.2 Stocktake of capabilities/resources

The Parkes 64m radio telescope[50] continues to be one of the world's most important telescopes for radio pulsar science, and spends roughly 50% of its time either surveying the sky for pulsars or timing them. The planned Ultra-Wideband (UWB) receiver, operating in the band from 700 MHz to 4 GHz, will maintain the world-leading status of Parkes for precision pulsar timing and gravitational-wave detection into the SKA era. The upgrade design is underway, and a LIEF grant was submitted in 2014 involving 7 Australian institutions.

7.3 New opportunities/requirements

New mid-scale National Facilities The Molonglo Observatory Synthesis Telescope[51] (MOST) is currently being reengineered to include a pulsar monitoring backend that exploits the entire primary beam of the 4.7×11 m modules of the array. It is envisaged that this system when complete will be able to monitor 500 pulsars per day by timing many pulsars at once using a 30 MHz band near 840 MHz.

The Murchison Widefield Array (MWA) has a tied array mode currently under commissioning that should be able to detect many 100s of pulsars at low frequencies and search for new scintillating pulsars using mapping techniques.

New International Facilities The MeerKAT [52] telescope, a precursor to the South African component of the SKA, will comprise 64 13.7 m offset Gregorian dishes, and will form a very high sensitivity pulsar telescope. The instrument is expected to be operational in a preliminary phase with 16 antennas by end of 2015, and with the full 64-dish array by end of 2016. Pulsar timing is one of two highest-priority MeerKAT Key Science Projects, and led by an Australian (Bailes). Its combination of large collecting area, wide bandwidths, excellent site and low system temperatures will make it an important pulsar timing facility leading into SKA phase I. The FAST radio telescope, a 500-m diameter Arecibo-style telescope, currently under construction

[50] http://www.parkes.atnf.csiro.au
[51] http://www.physics.usyd.edu.au/sifa/Main/MOST
[52] http://www.ska.ac.za/meerkat

in Guizhou Province, China[53], will also be a highly sensitive instrument for pulsar searching and timing. It is expected to be operational in 2017. The SKA itself will initially comprise of three separate telescopes, SKA-mid, SKA-low and the extended ASKAP telescope. SKA-mid will be a 192-dish extension of the MeerKAT telescope, ideal for pulsar timing and searching. SKA-low would be a very good pulsar survey and timing instrument with moderate backend additions to the baseline design. The extended ASKAP telescope may use its high sensitivity to identify scintillating radio sources, many of which may be pulsars.

The full SKA, nominally scheduled for construction circa 2020 will be an amazing pulsar facility and capable of monitoring and discovering 1000s of pulsars.

7.4 Suggested strategies and resourcing levels

The high sensitivity, wide bandwidth and excellent polarisation performance of the planned Parkes ultra-wideband (UWB) receiver will maintain the pre-eminent position of Parkes as an instrument for pulsar observations — and especially precision pulsar timing — into the SKA era. It will also be valuable for other science including studies of the Galactic magnetic field and the polarised Galactic background, spectral-line observations and VLBI. The Parkes 20-cm multi-beam receiver has been and continues to be an outstanding instrument for pulsar searches, with the discovery of about half the known pulsars to its credit. However, an advanced phased-array feed (PAF) will be needed to maintain the role of Parkes as a southern-hemisphere survey instrument into the SKA era. These instruments also open up the possibility of a real-time interferometer between ASKAP and Parkes, enabling high-resolution observations and accurate astrometry of ASKAP survey detections.

MOST could be upgraded to broader bandwidths by re-using technologies being developed for the Canadian Hydrogen Intensity Mapping Experiment[54] (CHIME). The MOST system is currently limited to 30 MHz of bandwidth and a single band of circular polarisation. The CHIME system offers 400 MHz of bandwidth and dual polarisation. Such an upgrade to MOST would likely cost approximately $2m but would make it over 20$\times$ more powerful for pulsar timing. The MOST upgrade would be excellent for continuum mapping of low surface brightness objects due to its short spacings, as well as baryonic acoustic oscillation work, where its field of view and spatial resolution would mean it easily outperforms the Green Bank Telescope[55] (GBT).

The MWA tied array beam mode should be finished in the near future, but an upgraded MWA might use more bandwidth and have a simpler back-end than the current coarse/fine grain filterbanks that limit high time resolution modes. A new completely digital backend for the MWA would make it easier to maximise its pulsar modes.

A supercomputer at the South African SKA site could be used as a pulsar backend for the

[53] http://fast.bao.ac.cn
[54] http://chime.phas.ubc.ca
[55] https://science.nrao.edu/facilities/gbt

MeerKAT telescope. This would require about $0.5m in capital and 2 EFT years to deploy. Australian engagement in the SKA is a national priority. The pulsar timing backend is being designed in Australia as part of the Central Signal Processor[56] (CSP) consortium.

References

[1] Manchester, R. N. et al. (2013), PASA, 30, e017

[2] Keith, M. J. et al. (2010) MNRAS, 409, 619

[3] Manchester, R. N. et al. (2013) CQGra, 30(22), #224010

[4] Shannon, R. M. et al. (2013) Science, 342, 334

[5] Kramer, M. et al. (2006) Science, 314(5796), 97

[6] Bhat, N. M. R. et al. (2008) Phys.Rev.D 77(12), #124017

[7] Freire, P. C. C. et al. (2012) MNRAS, 423(4), 3328

[8] Abbott, B. P. et al. (2010) ApJ 713, 671

[9] Verbiest, J. P. W et al. (2008) ApJ 679, 675

8 GRAVITATIONAL-WAVE ASTROPHYSICS

Gravitational waves are vibrations in space and time which propagate at the speed of light, and are a direct prediction of Einstein's equations of general relativity. It has taken decades of both theoretical and experimental effort to develop instruments with enough sensitivity to detect the predicted signals. Their direct detection is likely to happen in the first half of the next decade, through ground-based interferometric antennas and/or pulsar timing array experiments.

The first detection of gravitational waves from astrophysical sources will be a transformative event with the prospects to substantially alter international research priorities. As such, we consider this research area as deserving particular focus for this report. We present here a discussion following the structure of other sections, but also include (in appendix A) a more detailed statement of the scientific objectives of gravitational-wave science.

Matter, even in its most extreme form, is completely transparent to gravitational waves, implying they can be used to probe regions of the Universe beyond the reach of electromagnetic waves. For example, some of the most violent processes in the Universe – from the Big Bang itself, to supernova explosions and gamma-ray bursts – are hidden from electromagnetic imaging by the opacity of hot plasma. Gravitational waves, however, propagate freely without being scattered or absorbed. They carry a faithful record of the fundamental processes at play in the most extreme physical environments in the Universe. They can reveal the rippling surfaces of newly born black holes, the churning nuclear matter inside newly formed neutron

[56] http://www.skatelescope.org/skadesign/wp/csp

stars, the gravitational collapse that powers a supernova explosion, and the earliest moments of the Big Bang. Gravitational waves are the only means of observing some of these extreme environments.

Astrophysical gravitational wave signals are expected to occur over a wide range of frequencies, from 10^{-17} to 10^{4} Hz. Different frequency bands carry information about different sources and phenomena. Across this huge range there are complementary efforts at detection, with Australian researchers playing key roles.

In the audio band, a worldwide network of advanced ground-based interferometers like LIGO and Virgo are sensitive to signals from 10 Hz to a few kHz. In this band, signals are expected primarily from processes involving stellar mass black holes and neutron stars, with the added possibility of seeing waves from the big bang (1). Accurate timing of the signals enables locating the source by triangulation. The advanced detectors are designed to be able to detect frequent signals from the coalescence of binary neutron stars. These are the best predicted sources, and their discovery is highly likely in the first half of this decadal plan. In addition, there exists a wide range of other predicted discoveries summarised below. It is also recognized that gravitational wave science will inevitably uncover profound surprises, both fundamental and practical, as always occurs when a new spectrum is opened.

Memoranda of Understanding have been signed between LIGO and numerous telescopes covering the full electromagnetic spectrum, including four in Australia (AAO, MWA, SkyMapper, Zadko) as well as the Variables and Slow Transients (VAST) survey program with ASKAP. Real-time gravitational wave triggers will give source sky-locations (albeit with rather poor precision), prompting immediate follow-up of the most energetic, transient events in the Universe. Gravitational wave triggers of binary neutron star mergers may, for the first time, allow the full prompt emission of a gamma-ray burst to be seen in multiple wave-bands. Such "multi-messenger" astrophysics extends to the burgeoning field of particle astrophysics; e.g., neutrino bursts from supernovae carries unique information about the thermonuclear reactions and particle physics processes that occur inside the core of collapsing stars. Simultaneous gravitational wave and neutrino observations of nearby supernova will provide new insights into the formation of the chemical elements, the birth processes of neutron stars and black holes and enable new tests of the Standard Model of the fundamental forces.

The scientific impact of audio-band gravitational wave astronomy will be broad. Measuring the speed and polarization of gravitational waves will allow unprecedented tests of Einstein's theory of general relativity in the weak field, while simultaneous measurements of two or more frequency overtones from black hole ringing will test Einstein's theory in the strong-field regime. Binary neutron star coalescence and periodic signals from rotating neutron stars allow us to probe properties of bulk nuclear matter in conditions inaccessible to terrestrial experiments. Gravitational wave signals from coalescing neutron stars or black holes are standard sirens, allowing luminosity-distance redshift measurements independent of the cosmic distance ladder. And of course, whenever a new window is opened on the Universe, the most exciting prospect is the discovery of the unknown.

Pulsar timing arrays are sensitive to gravitational waves in the nanohertz band (about one cycle per annum). The primary sources for such waves are binary super-massive black holes in distant galaxies. As described in §7 above, this technique is currently being developed by three major groups around the world, with the Parkes Pulsar Timing Array (PPTA) playing a major role (2; 3).

Beyond the scope of the present plan is the proposed space-based laser interferometer detector concepts. In the frequency range of approximately one cycle per hour, eLISA is the chosen L3 mission within the ESA Cosmic Vision Program, with a tentative launch date of 2034. eLISA will be able to detect binary stars in our galaxy and stellar mass black holes falling into super-massive black holes.

8.1 Progress against objectives

The previous decadal plan (2006–15) identified the potential of gravitational wave astronomy, but (correctly) placed the first direct detection of gravitational waves beyond that decade. Furthermore it noted that:

> Australia's role in the international gravity-wave observatory is best supported through Australia's subscription to the international Advanced LIGO program. The Australian Consortium for Interferometric Gravitational Astronomy (ACIGA) is developing and testing techniques for next-generation advanced gravity-wave interferometers, and is well-placed to make a significant intellectual contribution to Advanced LIGO.

During the period of the last decadal plan significant progress was made towards these objectives by Australian researchers, and Australia's involvement in ground based gravitational wave detection has been sustained and substantial. In particular, university research groups have delivered and installed key physical components to Advanced LIGO:

a) Laser lock acquisition system (ANU)

b) Low-loss mirror coatings (CSIRO Centre for Precision Optics)

c) Hartmann wavefront sensors for thermal compensation system (UA)

d) In situ demonstration of squeezed light operation (ANU)

Australian research groups further developed four high-priority LIGO data analysis pipelines and tested them on initial LIGO data:

a) Periodic signals from young neutron stars (ANU, UM)

b) Periodic signals from accreting neutron stars (UM, Monash)

c) LOOC-UP optical electromagnetic follow-up (Skymapper) (ANU)

d) On-line real-time compact binary coalescence pipeline (UWA) (tested on Initial LIGO and Advanced LIGO engineering runs ER2, ER4, ER5)

Contributions were also made to the design of the 3rd generation Einstein Telescope detector, the notional successor to the "advanced"-stage detectors currently in development. Theoretical research was conducted productively on the fundamental physics of gravity, dense nuclear matter, GW sources, and the quantum theory of gravitational wave detectors.

During the period of the previous decadal plan two unexpected new opportunities also arose. First, the LIGO Laboratory made an offer (authorized by the USA National Science Foundation), for Australia to host one of the two duplicate Advanced LIGO interferometers at the Hanford, WA site on a 50/50 cost-share basis ($140m Australian share). Funding did not materialize, and thus the instrument was offered to India, which accepted the offer and is developing LIGO-India (see §8.3 below for further details).

Second, spectacular progress has been made towards the goal of detecting gravitational waves with a pulsar timing array (see also §7). Recent and on-going surveys have dramatically increased the known sample of low-noise millisecond pulsars, making it feasible to set up a Pulsar Timing Array based on observations of many pulsars spread over the celestial sphere. The Parkes Pulsar Timing Array (PPTA; 3), commissioned in 2005, is in effect a GW detector in the nHz band using the Earth as a test mass. It offers the possibility of making the first detection of GWs and recently placed the best limit on the stochastic GW background from supermassive black holes in distant galaxies (2).

8.2 Stocktake of capabilities/resources

The primary facility contributing to gravitational wave detection via pulsar timing arrays is the Parkes radio telescope, as discussed in §7. There is a broad science case for continuing support of this facility throughout the next decade, at least until the SKA is operational.

Here we focus on the facilities and resources contributing to kHz gravitational wave detection via interferometric detectors. The detectors themselves are located in the US and Europe, but substantial national research facilities exist. This includes 50+ researchers at UWA, ANU, UA, UM, Monash, CSU, CSIRO Precision Optics and CSIRO ICT, which represents > 5% of the membership of the international LIGO-Virgo Scientific Collaboration. A significant expansion of involved personnel within the electromagnetic astrophysics community is already underway with multiple MoUs signed between the LIGO-Virgo collaboration and Australian telescopes (see below). This expansion is projected to further increase significantly after the first gravitational wave detection.

National Facilities

a) Australian High Optical Power Facility at Gingin for investigating three-mode parametric interactions and parametric instability in optical cavities

b) Parkes radio telescope and shared PPTA infrastructure

c) Gravity Recovery and Climate Experiment (GRACE) Follow-On Mission Technology Development Centre

Current international Facilities As members of the LIGO-Virgo Scientific Collaboration (LVC), Australian researchers have full access to the following gravitational wave interferometers. These instruments will be operated in the upcoming decade as a worldwide network of detectors, possibly including one or more of the instruments under development.

1. Laser Interferometer Gravitational-wave Observatory[57] (LIGO) is the most sensitive of the current generation of ground-based interferometric instruments. It comprises two separate 4 km detectors at Hanford, WA and Livingstone, LA in the USA. LIGO has been operational in an "initial" phase over the past decade, and although no detections have been made, the detector has achieved it's target sensitivity, and several astronomically interesting upper limits have been developed. Advanced LIGO is currently being commissioned, with the first observation run expected in Q4 2015.

2. Virgo[58] is a 3 km interferometer located near Pisa, Italy. Virgo also had an operational "initial" phase over the last decade, and is currently being upgraded to Advanced Virgo.

3. GEO600[59] is a 600 m interferometer located in Germany. The shorter arm-lengths imply GEO600 is less sensitive than the LIGO/Virgo detectors, but has better capabilities at higher frequencies (> 2 kHz). GEO600 has been in "Astrowatch" mode since the initial LIGO and Virgo interferometers were shut down. It has successfully implemented light squeezing technology for a full year of observations, lowering the noise level by more than 1.5 dB.

International Facilities in Development The following international interferometers are at various stages of development, but are also expected to be taking science data before the end of the upcoming decade.

1. The Kamioka Gravitational Wave Detector (KAGRA) – installation has begun, with active operation scheduled for $\sim$2018. KAGRA is the first long-baseline cryogenic detector located underground. Cryogenics is used to reduce thermal noise and underground mitigates Newtonian noise.

[57] http://www.ligo.org

[58] http://www.ego-gw.it/

[59] http://www.geo600.org/

2. LIGO-India – proposed operation scheduled for $\sim$2020. This third Advanced LIGO detector will create a LIGO network with better source localization and sensitivity.

Electromagnetic follow-up instruments and/or analysis pipelines Several groups have explored or are developing the capability to promptly respond to reports of gravitational-wave detections, in order to identify the electromagnetic counterparts of these sources. Because the localisation ability of the current international network is so poor (typical error regions expected to be $\sim$ten square degrees in area) this is a challenging task for most observatories. Detection efficiency estimates suggest $\sim$1–10 detections per year for X-ray and optical afterglow for binary neutron star and neutron star-black hole mergers. However, the scientific payoff will be substantial, as only with an accurate position and measurements in other bands, observers will be able to achieve a full characterisation of the gravitational wave sources.

A low-latency gravitational wave "trigger-factory" has been developed at the UWA and implemented in LIGO. Here, the time between the arrival of a gravitational wave signal, and the real-time analysis of that signal has been reduced to ~ 10 s. This has significantly reduced the trigger-time for electromagnetic follow-up, and will subsequently increase the multimessenger detection efficiency.

In addition, development of computational infrastructure has focussed on providing the necessary computational power to search data both from interferometric detectors and pulsar timing arrays.

The LIGO-Virgo Scientific Collaboration has signed Memoranda of Understanding with numerous telescopes across the globe, to share real-time gravitational wave data, allowing for real-time electromagnetc follow-up. The following Australian facilities have signed these MoUs:

a) Skymapper and Zadko are respectively 1.35 and 1 m robotic telescopes capable of performing fast response optical follow-up of gravitational wave triggers.

b) The Anglo-Australian Telescope (AAT), at 4-m is the largest optical telescope in Australia.

c) The MWA is a low-frequency radio telescope that allows for transient detections with its voltage capture capabilities.

d) The ASKAP survey for Variables and Slow Transients also has wide-field survey capabilities that allows for the investigation of transient phenomena.

Computational Infrastructure LIGO and the PPTA share various computing infrastructure for GW data analysis. These include local resources:

a) Hardware: CPU, storage (Pawsey, Swinburne, NCI, VPAC)

b) Galaxy workflow management/collaborative e-tools (CSIRO ICT)

c) GPU systems (Pawsey, NCI)

As members of the LIGO-Virgo Collaboration, the Australian community have access to shared international computing resources dedicated to audio-band GW analysis, primarily of LIGO data. These clusters form the LIGO Data Grid:

1. Caltech IT: 3148 cores
2. LIGO Hanford Observatory: 2016 cores
3. LIGO Livingston Observatory: 2024 cores
4. MIT: 512 cores
5. ATLAS cluster: 1680 cores

Scientific Research Capabilities Expertise abounds in Australia in all areas of gravitational wave detection, including experimental physics, data analysis and theoretical astrophysics research. Each of these is outlined below:

Experimental research capabilities include

a) High power laser technology and high optical power interferometry; radiation pressure effects, instability control, diagnostics and control using three mode interactions; Advanced detector techniques for measurement below the standard quantum limit: optical springs and optical squeezing control; development of commercial sensors and isolators based on GW technology; ultrahigh performance filter cavities (UWA)

b) Quantum optics, interferometer control, complex optical metrology, next generation optical squeezing source control, low-frequency gravitational force sensors, fibre sensors and LIGO commissioning (ANU).

c) Wavefront sensors, adaptive optics, high-power lasers, long-wavelength lasers, LIGO commissioning (UA)

d) Noise suppression theory (Monash)

e) High-precision coating of large optics, surface flatness and roughness measurements (CSIRO Precision Optics)

Data analysis/observational research capabilities:

a) Pulsar Timing Array (CSIRO, Swinburne, Monash, UWA, UM)

b) LIGO periodic searches (ANU, UM, Monash)

c) LIGO multi-messenger triggers (ANU, UWA)

d) Stochastic gravitational wave background pipeline (CSU, UWA)

e) Supercomputing for gravitational wave science including graphics processing unit acceleration and collaborative e-science (virtual laboratory) tools (CSIRO ICT, UWA, UM, ANU)

Theoretical research capabilities

a) Gravitational Wave source physics for LIGO and PPTA (UM, Monash, UWA)

b) Signal processing theory (Monash, UM, UWA)

c) Advanced quantum measurement theory for second and third generation GW interferometers; development of quantum noise mitigation methods for advanced detectors (ANU, UWA)

Outreach:

a) Eureka-prize-winning Gravity Discovery Centre, Gingin

b) PULSE@Parkes (CSIRO)

8.3 New opportunities/requirements

The Advanced LIGO detectors are expected to start recording science data in 2015, with the Advanced Virgo detector coming on-line soon thereafter, and gravitational waves from coalescing neutron star binaries likely to be detected before 2020. Gravitational wave astronomy will thus be born.

Multi-messenger (EM, GW, and neutrino) observations using Australian facilities like Skymapper and SKA (trigger pipelines installed already; see above), and international facilities like the Palomar Transient Factory, will become part of the backbone of the new field of gravitational wave astronomy. Over 60 observatories worldwide (including the AAO, SkyMapper and the MWA) have signed MoUs with LIGO to be ready to follow-up on transient triggers from LIGO during the first science run (expected in 2015).

To take full advantage of these opportunities and of Australia's strong role in the international collaborations involved, several key issues must be addressed in the coming decade. Namely:

1. LIGO is adopting an open-access data policy post-first detection. How can Australian astronomy maximize the payoff from this opportunity?

2. Engagement (at what level, and in what form?) with other GW programs and facilities in the Asia-Pacific: LIGO-India, KAGRA (underground Japanese detector, now fully funded and proceeding to construction), and China.

3. Engagement with ex-astronomy communities, e.g. environmental sensing (GRACE) applying GW technology, particle physics (CoEPP, IceCube, dense matter), perhaps leading to joint ARC Centre of Excellence bids

4. Engagement with Australian space program, e.g. GRACE

During the next decade the imperative of a southern hemisphere detector for EM follow-up of GW events, GW/EM multi-messenger astronomy, and improved measurement of GW polarization components for probing the fundamental physics of the GW sources will be even more apparent. The Gravitational Wave International Committee (GWIC) Roadmap strongly recommends both the development of a southern hemisphere interferometer for detection in the audio band, and the ongoing development of rays as gravitational wave detectors. In particular, it recommends the "construction, commissioning and operation of the second generation global ground-based network comprised of instruments under construction or planned in the US, Europe, Japan and Australia…Instrumentation of comparable sensitivity to Advanced LIGO …is highly desirable in the Southern Hemisphere." (p 97).

The design of higher-sensitivity third-generation detectors and the development of technology for those detectors have started. Australia can assume a significant role in this development, further strengthening the argument for locating a detector in Australia. Construction of third generation GW detectors, e.g. the Einstein Telescope[60] (ET; approx. €1bn), is expected to commence after the first detection of GWs. These instruments will have sensitivity $\sim$100 times Initial LIGO, and rely on advanced quantum noise mitigation. Demonstration of squeezed vacuum injection in Advanced LIGO and GEO600 is a first step towards a broadband low quantum noise detector built on novel quantum measurement techniques. Australia has strong ties with the Einstein Telescope collaboration, opening opportunities for future contributions.

Furthermore the GWIC roadmap recomends "The continued development of an international pulsar timing array for the study of gravitational waves in the nano-Hertz band. This effort requires continued development of algorithms and data acquisition systems, and access to substantial amounts of time on the world's largest radio-telescopes." (p 98). A Pulsar Timing Array based on the SKA will play a key role in this detection (e.g. cosmological stochastic background from supermassive black hole mergers) over the next 10 years (see also the US Astro2010 Decadal Survey[61]).

Space-based gravitational wave science has been given a boost with eLISA being chosen as the L3 class mission for the European Space Agency, with a tentative scheduled launch of 2034. Although that timescale is outside the scope of this plan, Australia does have significant capability in satellite laser ranging through its involvement with the GRACE mission and the Space Environment Research Centre.

8.4 Suggested strategies and resourcing levels

To a first approximation, the recommended decadal strategies for GW astronomy in Australia are the same as those enunciated by GWIC in its Strategic Roadmap, and the USA Astro2010

[60] http://www.et-gw.eu
[61] http://sites.nationalacademies.org/bpa/BPA_049810

Decadal Review. The recommendations most relevant for the Australian community are the following:

1. **Australia should continue to contribute to the construction, commissioning and operation of Advanced LIGO, KAGRA and LIGO-India, while working with suitable countries to identify a consortium for the construction and operation of a southern hemisphere detector.**

   It is recommended that Australia should strengthen its significant activity in gravitational wave science and technology up until first detection. At this point, the construction of a southern hemisphere detector will likely become a global priority to ensure optimum signal localisation and enable electromagnetic telescopes to identify sources. After first detection, it is recommended that Australia put up a 20 – 30% share (>$120M) over 5 years to secure the construction of a third generation detector in Australia commencing in the second half of the decade, with the operation of that detector scheduled for the first half of the next (2026-2035) decade.

2. **A fundamental priority is the continued development of the Parkes Pulsar Timing Array and participation in the International Pulsar Timing Array for the study of gravitational waves in the nano-Hertz band.**

   This effort requires continued development of algorithms and data acquisition systems, and access to substantial amounts of time on the world's largest radio-telescopes. It is recommended that the Parkes radio telescope continue its enhancement program, including the development of next-generation receivers and backend instruments.

3. **Australia must continue to pursue a strong and ongoing international program of research in multi-messenger and gravitational wave astrophysics, directed towards deepening our understanding of gravitational wave observations.**

   It is necessary to invest in the development of gravitational wave and multi-messenger astronomers and the required data analysis and computing infrastructure. Efforts should also be directed towards coupling Australian supercomputing facilities deeply into the GW data analysis effort as a key partner in the first detection of GWs.

4. **A priority is to work in collaboration with existing design study teams to support the construction of the Einstein Telescope, expected soon after the first gravitational-wave discoveries have been made, circa 2018**

   It is necessary to work with design study groups internationally and organise meetings to assist the community to understand and establish science-driven requirements (e.g. frequency range, sensitivity) that would optimize the scientific potential of the network. This includes engagement with the series of planned GWIC workshops, each focused on the status and development of a particular critical technology for gravitational wave instruments. These workshops will help promote an exchange of ideas, provide visibility and encouragement to new efforts in critical areas of technology development, and help bring to bear the combined resources of the community on these problems.

5. **It is essential to increase interactions with other areas of astronomy as well as other relevant scientific communities (e.g. particle physics) and develop procedures that, beginning in the era of frequent ground-based detections of gravitational waves, will allow the broader scientific community to fully utilize information about detected gravitational waves.**

   The primary goal is to engage the interest of scientists in the work underway in gravitational wave research, and to foster collaboration and scientific exchanges, most importantly multi-messenger collaborations between the gravitational wave, electromagnetic and neutrino astronomy communities.

   Memoranda of understanding (MoU) have been signed between the Anglo-Australian Telescope, the Australian Square Kilometer Array Pathfinder (in particular the VAST survey), the Murchison Wide-Field Array, SkyMapper and the LIGO and Virgo Consortium (LVC) to use Australian facilities to do EM follow-up of GW candidate detections. Furthermore the TAROT-Zadko-Algerian National Observatory are currently completing an MoU with LIGO-Virgo for optical follow up: Zadko (1m robotic), TAROT[62] (2×25 m fast response telescopes), Aures (Algeria; several 50–60 cm telescopes; from 2017). Zadko and TAROT already operate as a network (CADOR) doing optical follow up of GRBs.

   It will also be necessary to develop an Australian Virtual Laboratory for Gravitational Wave Science, in collaboration with international partners, CSIRO, and the Australian All-Sky Virtual Observatory, to provide a stable, user-friendly interface to gravitational wave data and data analysis pipelines available to the whole Australian astronomy and physics communities when the open-access era begins.

6. **Australia should continue technology development for LISA and related missions.** eLISA currently has a programmed launch date of 2034 as an ESA L3 mission. Although this timeline is outside the scope of this DP, Australia has significant capability in satellite laser ranging through its involvement in the GRACE-Follow on observation mission, the Space Environment Research Centre and with a number of expatriates in JPL science and engineering positions. It is therefore recommended that Australia keeps a watching brief on this field and encourages continuing R&D supported through the ARC and other programs.

7. **The Australian community should further develop existing outreach programs focused**

[62] http://tarot.obs-hp.fr/tarot

on engaging public, school and political audiences with the excitement, promise and gains to society of the science and technology of gravitational wave astronomy.

References

[1] Abbott, B. P. et al. (2009), Nature 460, 990

[2] Shannon, R. M. et al. (2013) Science, 342, 334

[3] Manchester, R.N. et al. (2013) PASA, 30, #e017

9 THEORETICAL HIGH-ENERGY ASTROPHYSICS

The theoretical capabilities in this area depend on the presence and availability of suitably-trained theoreticians; access to national and international observing facilities; and the requisite supercomputer facilities. It is important to build up a critical mass of *both* observers and theoreticians to stimulate the usual interchange between observation and theory to the mutual benefit of both areas. We note the long-standing initiatives in observational high energy astrophysics at the University of Adelaide and more recent inititiatives at Monash and Curtin Universities. However, a critical mass in both observation and theory in the multitude of topics covered by high energy astrophysics is unlikely in any one institution. Hence, in order to stimulate the exchange of facts and ideas in this field good communication and networking is essential, for example via workshops in high energy astrophysics on a time scale of at least once a year. It is important that theoreticians not only interact with other astronomers in their own institutions but also in the wider astronomical community. National issues for theoretical astrophysics has been addressed in recent years by the Australian National Institute for Theoretical Astrophysics (ANITA), with a strategy of encouraging networking and interaction within and without the community. A basis for the discussions in this working group are the general principles laid out in *The ANITA Strategic Plan 2012-2015*[63].

9.1 Progress against objectives

High energy astrophysics was not specifically included in the previous decadal plan. However, we can report on the following achievements in this area over the period of the last decadal plan and their synergies with areas that represent traditional strengths in Australian astronomy.

1. High resolution global simulations of accretion disks using NCI supercomputer resources. ANU researchers (Parkin and Bicknell) made substantial advances in numerical accretion disk modelling through their work on "global" models, which are not subject to the artificial constraints imposed by "shearing box" computations. Beginning with an analytic

[63] http://anita.edu.au/2012/07/02/strategic-plan-for-theoretical-astrophysics-released

equilibrium disk, they developed and solved the perturbation equations for the linear magnetorotational instability (MRI) in the pseudo-relativistic Paczynski-Wiita potential. They compared the analytic results with computational results derived from the development of an initial equilibrium disk, excited by a variety of different modes and determined when the instability saturates, showing that the final quasi-steady state is independent of the excitation mode and confirming that the disk parameter, alpha, the ratio of turbulent stress to pressure saturates at approximately 0.04. Utilising 3D spherical Fourier spectra of the turbulent disk, they showed that the global simulations exhibit convergence to a steady state in which the only effect of increasing resolution is the extension of the power spectrum to high wave numbers - establishing that previous results implying a lour level of turbulence with increasing resolution are due to the unphysical influence of shearing box boundary conditions (16; 17).

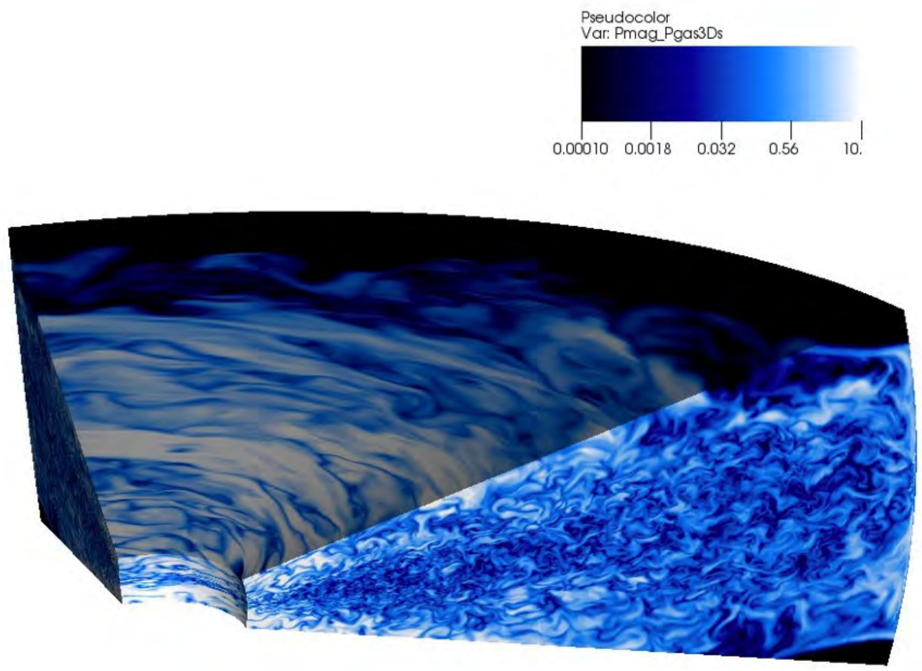

FIGURE 1: SLICE OF AN ACCRETION DISC SIMULATION SHOWING THE RATIO OF MAGNETIC PRESSURE TO GAS PRESSURE, HIGHLIGHTING THE TURBULENT STRUCTURE.

2. Comprehensive studies of relativistic jets and mildly relativistic winds examine the details of how these outflows interact with the interstellar medium of evolving galaxies (28; 27; 29; 30). See figure 2. This research includes models of the X-ray emission resulting from these interactions (24).

3. Theoretical modelling of combined radio and X-ray emission from extragalactic jets (7; 8).

4. Modeling of very high energy gamma ray emission (at TeV energies) from blazar jets in the region close to the black hole .

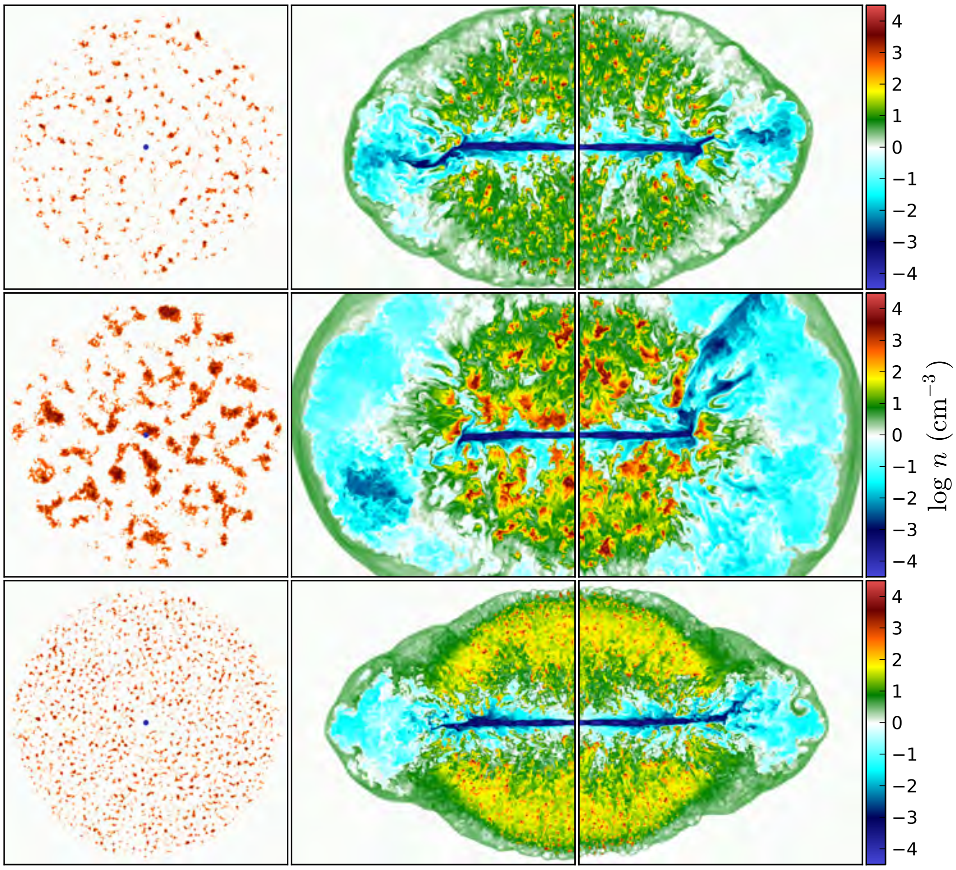

FIGURE 2: MONTAGE OF SIMULATIONS OF POWERFUL RELATIVISTIC JETS INTERACTING WITH THE INHOMOGENEOUS INTERSTELLAR MEDIUM OF EVOLVING GALAXIES.

5. Theoretical models of the high energy emission from ultra-luminous X-ray sources and the relationship between accretion disk and blazar emission (10; 5).

6. An example of a significant and ongoing multi-disciplinary astrophysics research campaign with a strong Australian flavour is centred on the recently-discovered 'Fermi Bubbles' (see the cover page figure). These structures are giant lobes emanating from the centre of the Milky Way and apparent examples of nuclear feedback operating in the Milky Way. They were discovered by independent researchers (23) analysing gamma-ray data provided by NASA's orbiting $Fermi$ telescope. Subsequently, observations conducted by an Australian and international team using the Parkes 'Dish' led to the discovery of the radio counterparts to the Fermi Bubbles (6). These radio counterparts are the second largest structures in the Galaxy, making their discovery all the more remarkable. From the theoretical side, Dr Roland Crocker, a recently appointed Future Fellow at ANU, worked with Carretti et al. to interpret the Parkes data. Crocker is now working with Prof. Geoff Bicknell and Dr Ralph Sutherland and others on deepening our understanding of these enigmatic structures (Crocker et al., ApJL in press).

7. Significant progress has been across several facets of neutron star interior modelling, the results of which will be crucial both for interpreting current PTA data and future SKA

radio data and for gravitational wave data analysis. The group lead by Melatos in Melbourne has pioneered the uses of several new techniques that have lead to an enhanced understanding of phenomena such as superfluid turbulence, radio pulsar timing noise and glitches, the dynamics of quantised vortices in neutron star interiors and the role of magnetic fields in gravitational wave emission mechanisms (15; 18; 19; 25; 31; 32). This effort requires close ties with the nuclear physics community, as the high densities and low temperatures of neutron star interiors allow a direct probe for aspects of the strong interaction that are not accessible in terrestrial laboratories.

8. There has also been significant progress understanding the brightness temperature of emission from Active Galactic Nuclei as it relates to the limit imposed by Inverse Compton scattering (11; 12) and the environment of their jets in the vicinity of the bright radio emission (13). This has been complemented by modelling of pan-chromatic variability and polarization data in gamma-ray blazars, particularly with respect to the connection between radio and gamma-ray emission (1; 9).

   A supporting thread involves the investigation of emission during the early stages of gamma-ray bursts (GRBs) (12), and the likelihood of observing prompt radio emission coincident with the gamma-ray emission observed in GRBs.

9. Although hadronic modelling of AGN has a long history, most modelling of AGN neglects accelerated protons and nuclei which are sure to be present. However, there has been a significant progress during the past decade, much of it by the Adelaide group or by their collaborators (see 14, and references therein). Also, simulations of acceleration/propagation of atomic nuclei followed by and the various interactions of energetic nuclei with target photons, i.e. photo-erosion, pion photoproduction (baryon resonance), and Bethe-Heitler pair production have been included (see 3, for) for details).

   Simulation techniques for in-situ acceleration of charged particles within the jet emission region using a "leaky box" model of particle acceleration has been used by Protheroe (20) and Allard & Protheroe (3) to model the acceleration and interactions of protons and heavier nuclei in presence of low-energy photon fields (CMB, EBL), as well as in the radiation field expected at hotspots in lobes of giant radio galaxies.

   An extension of the simulation method, originally introduced by Protheroe & Stanev (21), has recently been made by Ahlers (2) which allows rapid simulation of the angular scale of gamma-ray halos around individual AGN. Using a different approach, Venters & Pavlidou (26) have examined the angular fluctuations in the simulated gamma-ray sky as a function of energy expected for different strengths of the IGMF but this recent work relies on analytic approximations in going from 1D to 3D cascades.

   Major progress has been made in the last decade in cascade simulations where following large numbers of particles in a simulation becomes impractical. This is by using Monte

Carlo thinning technique and this has allowed simulation of particles at all energies in a cascade from the injection energy of 1 TeV right down to eV energies (4).

9.2 Stocktake of capabilities/resources

Research which is envisaged in the next decade is based upon the development of the above achievements together with increased collaboration involving theoreticians and national and international groups of high energy observers.

Accretion disk physics. A major goal in this area is the development of efficient radiation hydrodynamics codes that will finally be able to elucidate the structure of realistic accretion disks and the connection between accretion disks, jets and winds. This entails the incorporation of general relativity so that the role of accretion disk-driven outflows and ergosphere-driven outflows from black holes can be assessed. This work connects strongly to observational work on X-ray binaries and active galactic nuclei together with the general problem of the black hole fundamental plane.

Blazar modelling. Future research plans involve the origin of high-brightness temperature emission in Active Galactic Nuclei. Related problems are the origin of bright gamma-ray emission observed in blazars, the interpretation of its variability and the modelling of the high energy emission to deduce reliable parameters such as density and magnetic field for jets close to the parent black hole.

AGN feedback. The ANU group has established itself as a leader in this area and will continue its work on the interaction between relativistic jets and the inhomogeneous interstellar medium with more detailed physics (molecular cooling, non-thermal cooling, estimation of Stokes parameters, estimation of absorption, etc.) to further our understanding of the relationship between jet feedback and its relation to the evolution of galaxies and the radio luminosity function.

Understanding the activity of the Milky Way's nucleus in a cosmological context. From observations of external galaxies, it is clear that activity occurring within galactic nuclei must be communicated to much larger scales in order to regulate the star-formation occurring in those galaxies (e.g. 22). At the most basic level, the Fermi Bubbles and the coincident radio lobes discovered with Parkes represent the signatures of such nuclear feedback as it occurs locally. It is still a matter of active debate, however, whether the bubbles were inflated by recent activity of the Galaxy's central, super-massive black hole or, on much longer timescales, by the nuclear star formation occurring around it. In general, we expect a complicated interrelationship between nuclear star-formation and black hole activity: while both require accretion of gas into the nucleus, according to our currently-incomplete understanding, either might inhibit or promote the other depending on circumstances. Accurate modelling of nuclear feedback is crucially important in large-scale, cosmological simulations that seek to understand the star-formation history of the Universe. By definition, the Galactic Centre represents our closest view of a galactic nucleus. It thus provides, in principle, ground truth for theoretical and numerical modelling of nuclear feedback in star-forming, spiral galaxies.

From these considerations, two important desiderata emerge:

- Deeper, multi-wavelength Galactic Centre observations combined with self-consistent modelling of the energy and mass flows inferred from these observations will be crucial to our understanding of cosmology.
- Deeper observations of other galaxies in search of external analogues of the Fermi Bubbles currently push the state of the art because these structures and their multi-wavelength emissions are relatively dim. However, such observations are ultimately necessary if we are to understand exactly how peculiar our own Galaxy is. They will become possible with the coming generation of huge astrophysical instruments (SKA, CTA).

Ultra high energy cosmic rays. The Adelaide theory group will investigate the connection between active galactic nuclei (AGN), ultra-high energy cosmic rays (UHECR) and the inter-galactic magnetic field (IGMF). They will conduct non-linear time-dependent simulation of non-thermal AGN spectra following injection of arbitrary spectra of accelerated electrons and nuclei. AGN are extreme astrophysical objects with tremendous energy outputs, some of which is channelled into the production of UHECR. Whether the UHECR, which are astrophysical protons or nuclei with energies extending to at least 10^{20} eV (16 joules), are predominantly low-mass nuclei (protons) or much heavier (iron) is a hot topic with varying results from different experiments. The UHECRs produced in the sources give different signatures in gamma rays and neutrinos depending on their composition and source environments. In addition, after the UHECRs escape to intergalactic space, they propagate and lose energy via different processes that also depend on their composition and the energy densities of background photon fields and inter-galactic magnetic fields (IGMFs), similarly producing distinctive electromagnetic and neutrino signals.

During the next decade the Adelaide group and collaborators in the USA, France, Austria and Greece will conduct the most comprehensive modelling to date of the production of the UHECR, gamma rays, and neutrinos in the extreme astrophysical environments of AGN and GRB, together with the expected output in broadband electromagnetic radiation, UHECR and neutrinos. They plan to improve AGN modelling, predict diffuse UHECR, neutrino and gamma ray diffuse fluxes, and model neutrino, gamma-ray and radio halos around sources to probe the nature of the IGMF. They also will continue their involvement in UHE cosmic ray and neutrino astronomy through modelling the detection by SKA to bursts of nanosecond radio pulses from the moon when neutrino and UHECR hit it. The predictions from their modelling will be di-

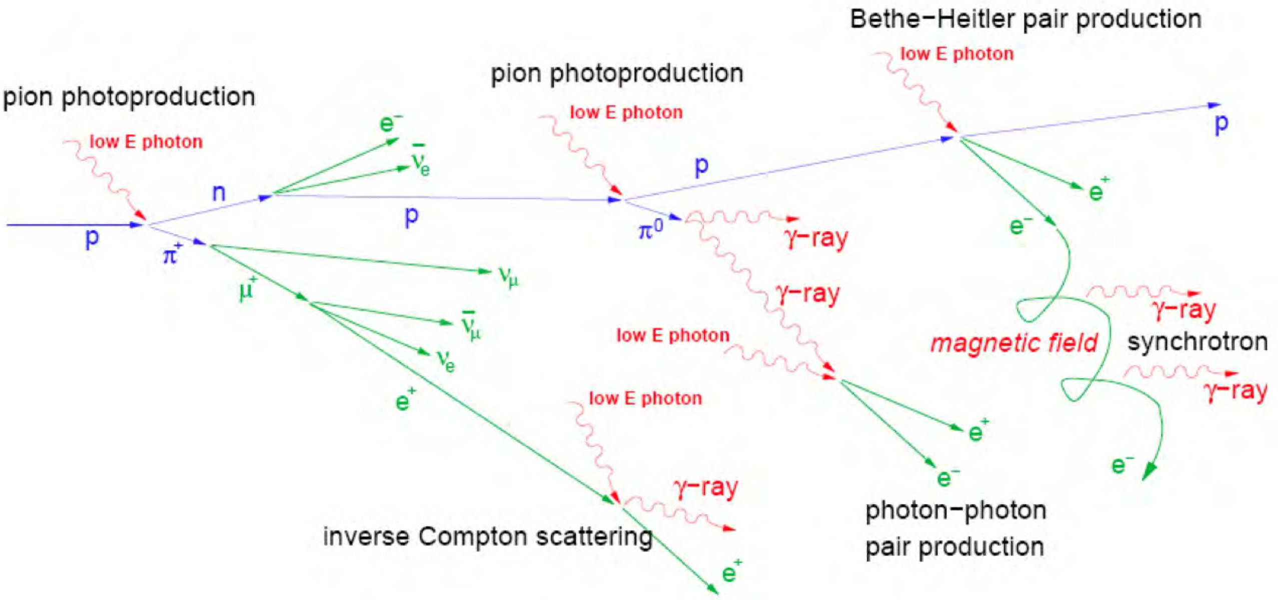

FIGURE 3: CARTOON SHOWING SOME OF THE IMPORTANT PROCESSES FOR NON-THERMAL RADIATION AND INTERACTION OF UHECR.

rectly comparable with data from existing facilities and those coming on-line during the next decade, such as UHECR experiments (Pierre Auger Observatory, HiRes, Telescope Array, JEM-EUSO, SKA-lunar), gamma-ray experiments (Fermi LAT, CTA), and neutrino experiments (Ice-Cube, Askaryan Radio Array) and radio telescopes (Square Kilometre Array).

Table 1 summarises the infrastructure in hunman capital and phsyical resources available to theoreticians in high energy astrophysics.
NCI: National Computational Infrastructure
MAS: Merit Allocation Scheme

9.3 New opportunities/requirements

New opportunities involve

1. The capacity to appoint new staff in the area of high energy astrophysics
2. The maintenance and development of supercomputing facilities for high resolution, three-dimensional simulations.
3. An independent theoretical astrophysics postdoctoral scheme to maintain adequate staffing levels required for participation in large scale international projects (e.g. LIGO, SKA etc..). This is also a priority in the ANITA strategic plan.

9.4 Suggested strategies and resourcing levels

New staff. As staff retire there is the opportunity to appoint new staff in this area, which is highly visible internationally. The appointment of high energy theoreticians capable of utilis-

Institution	Infrastructure	Human resources
Australian National University	Partner share NCI	3 academic staff, associated posdoctoral research associates and students
University of Melbourne	Multiple numerical simulation tools; Access to NCI via MAS and ASTAC	1 staff member and students, 2 postdoctoral research associates.
Monash University	Access to MASSIVE supercomputer and NCI via MAS and ASTAC; numerical simulation codes	3 staff members, associated posdoctoral research associates and students
University of Adelaide	Access to NCI via MAS and ASTAC	3 academic staff, associated posdoctoral research associates and students
Curtin University	Supercomputing access via NCI MAS, ASTAC and Pawsey Centre	1 academic staff and associated postdoctoral research associate.

TABLE 1: SUMMARY OF INFRASTRUCTURE AND HUMAN RESOURCES IN THEORETICAL HIGH ENERGY ASTROPHYSICS

ing the supercomputing resources available in this country is an important strategy as is the appointment of theoreticians who have been trained in leading institutions overseas.

Participation in international observational projects. Access to the latest data is essential for theoretical progress. Therefore, opportunities for Australian participation in outstanding observational projects should be explored whenever possible. One such project is the *Cerenkov Telescope Array* which is the successor to the highly successful HESS and MAGIC very high energy gamma ray telescopes.

Leverage of international collaborations. The provision of critical (theoretical or modelling) expertise is a good strategy to leverage influence in large experimental collaborations where Australia otherwise has a low level of financial commitment.

Theory postdoctoral fellowships The creation of a dedicated theoretical astrophysics postdoctoral fellowship and/or a national centre for theoretical astrophysics is crucial if Australia is to maintain strong and constant staffing levels and ensure its continued participation in large scale international projects such as LIGO and SKA. This is also a priority in the ANITA strategic plan.

References

[1] Abdo, A. A., Ackermann, M., Ajello, M., Axelsson, M., Baldini, L., Ballet, J., Barbiellini, G., Bastieri, D., Baughman, B. M., Bechtol, K., & et al. 2010, Nature, 463, 919

[2] Ahlers, M. 2011, Phys. Rev. D, 84, 063006

[3] Allard, D. & Protheroe, R. J. 2009, A&A, 502, 803

[4] Alvarez-Muñiz, J., James, C. W., Protheroe, R. J., & Zas, E. 2009, Astroparticle Physics, 32, 100

[5] Bicknell, G. V. & Wagner, S. J. 2011, A&A, 526, 61

[6] Carretti, E., Crocker, R. M., Staveley-Smith, L., Haverkorn, M., Purcell, C., Gaensler, B. M., Bernardi, G., Kesteven, M. J., & Poppi, S. 2013, Nature, 493, 66

[7] Godfrey, L. E. H., Bicknell, G. V., Lovell, J. E. J., Jauncey, D. L., Gelbord, J., Schwartz, D. A., Perlman, E. S., Marshall, H. L., Birkinshaw, M., Worrall, D. M., Georganopoulos, M., & Murphy, D. W. 2012, ApJ, 755, 174

[8] Godfrey, L. E. H., Lovell, J. E. J., Burke-Spolaor, S., Ekers, R., Bicknell, G. V., Birkinshaw, M., Worrall, D. M., Jauncey, D. L., Schwartz, D. A., Marshall, H. L., Gelbord, J., Perlman, E. S., & Georganopoulos, M. 2012, ApJL, 758, L27

[9] Hayashida, M., Madejski, G. M., Nalewajko, K., Sikora, M., Wehrle, A. E., Ogle, P., Collmar, W., Larsson, S., Fukazawa, Y., Itoh, R., Chiang, J., Stawarz, Ł., Blandford, R. D., Richards, J. L., Max-Moerbeck, W., Readhead, A., Buehler, R., Cavazzuti, E., Ciprini, S., Gehrels, N., Reimer, A., Szostek, A., Tanaka, T., Tosti, G., Uchiyama, Y., Kawabata, K. S., Kino, M., Sakimoto, K., Sasada, M., Sato, S., Uemura, M., Yamanaka, M., Greiner, J., Kruehler, T., Rossi, A., Macquart, J. P., Bock, D. C.-J., Villata, M., Raiteri, C. M., Agudo, I., Aller, H. D., Aller, M. F., Arkharov, A. A., Bach, U., Benítez, E., Berdyugin, A., Blinov, D. A., Blumenthal, K., Böttcher, M., Buemi, C. S., Carosati, D., Chen, W. P., Di Paola, A., Dolci, M., Efimova, N. V., Forné, E., Gómez, J. L., Gurwell, M. A., Heidt, J., Hiriart, D., Jordan, B., Jorstad, S. G., Joshi, M., Kimeridze, G., Konstantinova, T. S., Kopatskaya, E. N., Koptelova, E., Kurtanidze, O. M., Lähteenmäki, A., Lamerato, A., Larionov, V. M., Larionova, E. G., Larionova, L. V., Leto, P., Lindfors, E., Marscher, A. P., McHardy, I. M., Molina, S. N., Morozova, D. A., Nikolashvili, M. G., Nilsson, K., Reinthal, R., Roustazadeh, P., Sakamoto, T., Sigua, L. A., Sillanpää, A., Takalo, L., Tammi, J., Taylor, B., Tornikoski, M., Trigilio, C., Troitsky, I. S., & Umana, G. 2012, ApJ, 754, 114

[10] Jolley, E. J. D., Kuncic, Z., Bicknell, G. V., & Wagner, S. 2009, MNRAS, 400, 1521

[11] Macquart, J.-P. & de Bruyn, A. G. 2006, A&A, 446, 185

[12] —. 2007, MNRAS, 380, L20

[13] Macquart, J.-P., Godfrey, L. E. H., Bignall, H. E., & Hodgson, J. A. 2013, ApJ, 765, 142

[14] Mastichiadis, A., Petropoulou, M., & Dimitrakoudis, S. 2013, MNRAS, 434, 2684

[15] Mastrano, A., Melatos, A., Reisenegger, A., & Akgün, T. 2011, MNRAS, 417, 2288

[16] Parkin, E. R. & Bicknell, G. V. 2013, ApJ, 763, 99

[17] —. 2013, MNRAS, 435, 2281

[18] Payne, D. J. B. & Melatos, A. 2007, MNRAS, 376, 609

[19] Peralta, C., Melatos, A., Giacobello, M., & Ooi, A. 2006, ApJ, 651, 1079

[20] Protheroe, R. J. 2004, Astroparticle Physics, 21, 415

[21] Protheroe, R. J. & Stanev, T. 1993, MNRAS, 264, 191

[22] Scott, N. & Graham, A. W. 2013, ApJ, 763, 76

[23] Su, M., Slatyer, T. R., & Finkbeiner, D. P. 2010, ApJ, 724, 1044

[24] Sutherland, R. S. & Bicknell, G. V. 2007, ApJS, 173, 37

[25] van Eysden, C. A. & Melatos, A. 2010, MNRAS, 409, 1253

[26] Venters, T. M. & Pavlidou, V. 2013, MNRAS, 432, 3485

[27] Wagner, A. Y. & Bicknell, G. V. 2011, ApJ, 738, 117

[28] —. 2011, ApJ, 728, 29

[29] Wagner, A. Y., Bicknell, G. V., & Umemura, M. 2012, ApJ, 757, 136

[30] Wagner, A. Y., Umemura, M., & Bicknell, G. V. 2013, ApJl, 763, L18

[31] Warszawski, L. & Melatos, A. 2008, MNRAS, 390, 175

[32] —. 2011, MNRAS, 415, 1611

10 TIME-DOMAIN ASTROPHYSICS

Transient sources are one of the main areas of research of the Australian high-energy community. Short-timescale transient events are associated with the highest energy density events in the Universe. They provide nature's ultimate laboratory, where matter under extreme conditions displays properties that probe physical regimes which far transcend the range achievable in terrestrial experiments. Even the mere existence of such impulsive emission in some instances can transform our understanding of the behaviour of matter and space-time under the most extreme conditions.

A spate of recent discoveries of a new kind of fast transient over the past five years underscores the potential scientific return from unexplored areas of the transient parameter-space. The Parkes radio-telescope discovered a handful of examples of a remarkable new class of extremely bright and short-duration (millisecond timescale) transients called Fast Radio Bursts (FRBs) Thornton et al. (11). This result is a direct result of investment in Australian radio pulsar research infrastructure over the period spanned by the previous Decadal plan.

This transients renaissance is being propelled by three key advances: i) an order of magnitude increase in telescope field of view, enabling access to rare events ii) increases in telescope sensitivity, enabling access to fainter events iii) advances in high-speed computing, allowing us to take advantage of i) and ii).

Neutron star and black hole X-ray binaries, cataclysmic variables, magnetar flares, gamma-ray bursts, supernovae, tidal disruption events are all candidate sources, and offer great potential for breakthrough discoveries. One thing those classes of objects have in common is that their most violent and energetic behaviour is more likely to be detected first in the X-ray or gamma-ray bands, partly because high-energy photons come mostly from the region closer to the central engine (so, they are produced on the shortest timescale), and partly because the X-ray sky is less crowded than the optical sky, which makes transient outbursts easier to identify. Currently, such high-energy transient events are usually identified and monitored with the NASA/ESA *Swift* satellite and the Japanese detector MAXI on the International Space Station. However, such transient phenomena require prompt follow-up in other bands. For example, the high-energy flash from a short gamma-ray burst may last only a few seconds, but we can then study the rise of the optical emission from the shock produced when the blast wave from the explosion impacts the surrounding interstellar medium. By comparing the luminosity in the different bands, and the time delay between the emission components in X-rays, optical and radio, we can understand the physics of those systems.

In the radio band, Parkes, ATCA, ASKAP, MWA and SKA Phase I will provide sufficient coverage, but ground-based optical coverage is somewhat limited for Australian observers. The kind of telescope that is most useful for prompt follow-up studies (spectroscopy and multi-colour photometry) is a 2-m class automated instrument like the Liverpool Telescope (Canary Islands) or the Faulkes Telescopes (Hawaii and Siding Spring), or the partly automated 2.2-m GROND telescope (La Silla): all facilities to which the Australian community unfortunately does not have direct access. Even smaller telescopes, such as the SMARTS telescopes at Cerro Tololo, the 1.2-m Oschin Telescope at Palomar Observatory (used by the Palomar Transient Factory Project), the 1.2m Mercator telescope in the Canary Islands, the 1.2m Euler Telescope at la Silla, are great use for photometric follow-up studies of high-energy transients. Here, the University of Tasmania's Bisdee Tier 1.3m telescope will be a very welcome new entry in this class (both for GRB follow-up and X-ray binary work), when it overcomes its teething problems, but the only new one in Australia at this stage. UWA's recently refurbished 1-m robotic Zadko Telescope near Perth has been performing triggered deep follow-up (to 21st mag) of GRB Swift alerts since 2009, and is the most successful Australian-operated facility for GRB afterglow lightcurve studies. Its core science theme is relative photometry of rapid time varying sources, so its sea level location has only a minor effect on the facility's capability for this work; however, its location and modest aperture make it less suitable for optical-counterpart studies of X-ray binary outbursts. For GRBs and SNe, outstanding discoveries have been made with even smaller but fast-slewing telescopes equipped with state-of-the art CCD cameras: for example the twin 25-cm robotic TAROT telescopes (at Calern in Southern France, and at La Silla). In order to be competitive for high-energy transient detections, such small telescopes require slewing times of tens of degrees per second, and CCD readout times of a few seconds.

Considering the prominent role that transient detection has in the MWA/ASKAP/SKA plans (e.g., Murphy et al. 2013, PASA, 30, 6), there is a shared request in the Australian high-energy community that rapid-response optical surveys of the transient universe are not completely sacrificed in favor of large telescope surveys of the deep universe. Building a new 2-m robotic telescope for transient monitoring was an option recommended by several astronomers; as a plan B, building small TAROT-like robotic telescopes here and trading some of our large time available on radio facilities (MWA, ASKAP, SKA) for access quotas on non-Australian transient-sky 1.3-m class telescopes. For the same reasons, it was also recommended that the AAT retains the possibility of target-of-opportunity override programs for transients, as a long-term strategic plan (with the WHT offering a similar ToO policy in the northern sky), without the need to apply for Director's Discretionary Time every time a trigger arises.

Furthermore, rapid-response optical follow-ups do not necessarily need to be triggered by X-ray or Gamma-ray transients. For example, the coordinated effort between the LOFAR radio interferometer and the Panoramic Survey Telescope & Rapid Response System (PanSTARRS) is aimed at finding optical counterparts to radio-identified transients, as well as radio counterparts of optically identified ones; PanSTARRS is a system of four automated 1.8-m optical telescopes in Hawaii. Radio transient programs with the MWA and the SKA would be greatly enhanced if they were associated with an Australian equivalent of PanSTARRS for the Southern sky.

Australian astronomy has traditionally relied on excellent local facilities, coupled with geographical advantages. The lack of Australian sites with consistent sub-arcsecond seeing has killed any hopes of building 8-m class telescopes here; however, the transient sky is one of the few areas where we can still do cutting-edge science with 1.5 to 2-m telescopes in average seeing, and therefore an area where it still makes sense to build new telescopes in Australia, using Australian technology and guaranteeing larger access to local scientists. Australia has lost its geographical latitude advantage (because the Southern sky can be observed now from Chile with better seeing and larger telescopes), but it still retains a longitude advantage for transient and rapidly variable sources, because there will always be sectors of sky only visible from Australia for a few hours a day; therefore, a program of optical transient follow-ups from Australia will make the most of this advantage and is guaranteed to be part of every major discovery in the field. In addition, access to smaller telescopes is still an essential step for the training of students and postdocs, and for testing the design and implementation of new technology and new instruments. Finally, such telescopes have added value for outreach purposes (eg the very successful Faulkes telescopes funding scheme).

Below we describe some specific science motivations relevant to Australia's future participation in time-domain astrophysics

10.1 SCIENCE MOTIVATION

Time-domain astrophysics is not limited to purely electromagnetic techniques, but exemplifies the "multi-messenger" approach (see §11). Energetic, strongly gravitating objects like black holes and neutron stars are some of Nature's most potent particle accelerators, as well as being likely sources of gravitational waves, detectable by next-generation "advanced" detectors (see §8). Below we describe some science drivers for pursuing time-domain, multimessenger astrophysics.

10.1.1 SUPERNOVAE

The neutrino burst from a supernova carries unique information about the thermonuclear reactions and particle physics processes that occur inside the core of a collapsing star. Huge detectors like IceCube (see §4), where a cubic km of the Antarctic ice cap is instrumented to detect neutrinos, will be on line at the same time as the advanced gravitational wave detector network (see §8). Simultaneous gravitational wave and neutrino observations of a nearby supernova will provide new insights into the formation of the chemical elements, the birth processes (and resulting spins and magnetization) of neutron stars and black holes, and enable new tests of the Standard Model of the fundamental forces (1). The detection of a continuous gravitational wave source or memory event with the PPTA would trigger a multiwavelength study using all available instruments in an attempt to determine the nature of the host galaxy.

10.1.2 AGN FEEDBACK

Over the past decade, the case for AGN feedback playing a critical role in structure formation has become widely established, based on a wide range of arguments (45). There are two distinct modes, quasar mode, when an AGN's radiation has a direct impact on its surroundings, and radio mode, when power from an AGN is funnelled via radio jets and lobes into its surroundings. However, the mechanisms of both modes of feedback remain poorly understood. This has motivated a resurgence of interest in AGN, often using multiwavelength astronomy. X-ray observations have played a critical role, since they probe close to the AGN, providing the best means for determining whether an AGN is currently active.

AGN are powered by accretion onto supermassive black holes in the nuclei of galaxies. X-ray binaries are powered by accretion onto far smaller black holes. An important development in recent years has been the use of stellar mass black holes as analogues for understanding accretion in AGN. State transformations that occur on timescales readily accessible to observations in stellar mass black holes are far too slow to be observed in AGN. For example, X-ray binaries are being used to study the relationship between instantaneous accretion rate and radio jet formation (*eg*50). This has given impetus and significance to the study of stellar mass black holes that will continue into the coming decade.

10.1.3 GRAVITATIONAL WAVE SOURCES

Gravitational wave astronomy and astrophysics are very active areas of research (see §7, §8), and offer the possibility of ground-breaking discoveries not just for astronomy but for fundamental physics. A key objective for the next decade is to identify electromagnetic counterparts of such events. As the Mid-Term Review clearly stated, "For astronomers, it is essential to be able to identify the source responsible for gravitational wave emission, determine its characteristics, and place it among the classes of known objects." (p. 24) Among the astrophysical events that are predicted to produce electromagnetic signals alongside gravitational waves are supernovae, neutron star-neutron star and neutron star-black hole mergers. Prompt optical detection and follow-up will be essential for those events.

The LIGO/Virgo Scientific Collaboration (LVC) plans to start taking data in 2015, with the sensitivity gradually improving over time. The first four gravitational wave triggers will be released to partners who have signed a Memorandum of Understanding (MoU) with the LVC, with future high-confidence alerts being released promptly to the wider community. Following up gravitational wave events to detect their electromagnetic counterparts will be a key goal for the high energy and fundamental astrophysics community. With the wide fields of view of new radio facilities such as MWA, ASKAP, SKA1-low and SKA1-survey, the radio community can make an important contribution, localising candidate counterparts to much greater accuracy than the 5–20 square degree error boxes provided by the LVC, and allowing detailed follow up with narrower-field instruments.

Many of the general considerations discussed for the optical counterparts of high-energy transients apply also to putative optical counterparts of gravitational wave triggers: small robotic telescopes are more efficient than larger telescopes. In fact, for gravitational wave detections, the uncertainty in the initial position may be of order of one degree, much larger than for X-ray and Gamma-ray transients. Therefore, a large field of view is also an essential requirement. Detection of a candidate gravitational wave signal would trigger world-wide alerts to optical detectors such as the Palomar Transient Factory, Pi of the Sky, QUEST, ROTSE III, TAROT, and the Liverpool Telescope; in Australia, SkyMapper and the Zadko Telescope would be triggered. QUEST and TAROT are probably the best example of fast, large-area detectors specifically designed for this research. TAROT was already mentioned in relation to high-energy transients; the QUEST camera is mounted at the prime focus of the 1.2-m Schmidt telescope at Palomar, and covers 9.6 sq deg of sky. As for high-energy transients, the consensus among colleagues in the field (especially at UWA and ANU) is that Australia can be at the forefront of this field by investing in small, fast-response robotic telescopes.

10.2 TRANSIENT SURVEYS

Excluding follow-up observations, surveys are a key activity to detecting transients. There are a limited number of dedicated surveys aimed at sources of interest to the high-energy community with strong Australian involvement. However, a number of groups are routinely using high-energy data from international high-energy surveys or are taking a pan-spectral approach and studying high-energy events observed in lower energy surveys (e.g. optical, radio). Below we present a brief overview of the current and upcoming surveys focussing on transients.

10.2.1 X-RAY SURVEYS

The X-ray instrument eROSITA[64] is set to perform the first all-sky imaging survey in the X-ray range 0.5–10 keV[65]. Set for launch in 2015, this instrument will map the large scale structure in the Universe by observing the hot intergalactic medium of thousands galaxy clusters and the hot gas in filaments between clusters (10). It should detect all obscured accreting black-holes in nearby galaxies, up to several million new distant active galactic nuclei and study the physics of galactic X-ray source populations, supernova remnants and X-ray binaries.

CAASTRO is set to benefit from an MoU agreement with eROSITA which will allow members unique access to eROSITA and CAASTRO data for pre-defined approved projects that a) require both data sets and b) which pursue unique science programs. This agreement will present opportunities for joint projects for both postdocs and students.

The University of Sydney are providing funding to build collaborations with US researchers for radio follow-up of Active Galaxies detected with the NuSTAR X-ray satellite. This instrument, which has significantly improved sensitivity in the 3 –- 80 keV over previous instruments, will complement radio observations of Active Galaxies and should prove a useful probe of both the feedback mechanisms of an active galaxy and the subsequent impact on its surroundings.

10.2.2 GAMMA-RAY SURVEYS

Since H.E.S.S operations began in 2003 (H.E.S.S. II has functioned since July 2012) 9415 hours of data have been taken and discoveries include over 80 new VHE γ-ray sources, of which 19 are extragalactic. The H.E.S.S. Galactic Plane survey (GPS) has been a core component of the observation program since 2004 and has detected 60 galactic objects including pulsar wind nebulae, supernova remnants and γ-ray binaries (1).

The Cherenkov Telescope Array (CTA, 2) is a next generation ground-based instrument that will improve over previous experiments (HESS, VERITAS, MAGIC) with increased sensitivity, angular resolution ($\sim 2'$ at TeV), wider energy coverage (~ 30GeV – 300TeV) and a larger field of view (6°-8°). This project will consist of two arrays: a southern hemispheric array focusing on Galactic sources and a northern hemispheric array on extragalactic. The wide fields of view of many CTA telescopes will be highly beneficial for extensive surveys of our galaxy and beyond. Six Australian universities joined CTA as an associated party in 2013. Full CTA membership will require some contribution towards construction costs but will provide opportunities for both

[64] http://www.mpe.mpg.de/eROSITA

[65] it has a sensitivity 30 times greater than ROSAT in the 0.5-2 keV band

contribute towards the final array design and subsequent access to observation time with the CTA.

At lower energies < 400 keV the detection of gamma-ray bursts (GRBs) is a rapidly emerging area. It has advanced in recent years by the multi-wavelength observations of *Swift* and Fermi detected bursts that have shown GRBs to be the most luminous[66] and distant transient events in the Universe. The accumulation of around 200 redshifts has led to opportunities in using these bursts as cosmological probes. As part of the France-Italy GAmma Ray burst afterglow Observation collaboration (*FIGARO*, 5), UWA involvement has used existing catalogue data for a number of statistical population studies including unravelling the selection bias that plagues the redshift data.

10.2.3 RADIO SURVEYS

Over the next five years, both the $50mn low-frequency MWA and the Australian SKA Pathfinder (ASKAP), under the auspices of the Commensal Real-time ASKAP Fast Transients survey (CRAFT[67]) collaboration, have the potential to be ground-breaking transient factories by virtue of their large fields of view and high sensitivity. By 2020 and onwards the SKA itself, particularly its low-frequency component, will commence operation as a formidable transients detection machine. The field of view of the low-frequency aperture arrays, namely the MWA and SKA-low ($>>$100 sq. deg.), both located in Western Australia, make these ideal transients detection instruments. Additional detection capability at frequencies $>$600 MHz is to be provided by SKA-mid, which will commence construction in South Africa by 2016. Construction of these telescopes needs to be complemented by investment in back-end computational resources. The detection of transients is highly technology-driven, and only recently have advances in computational power and I/O bandwidth made it feasible to exploit these instrumental capabilities at the high time resolution necessary to detect fast radio transients.

An important new capability for electronically steered instruments[68] such as the MWA and SKA-low is the ability to retroactively point to a location on the sky in response to an event trigger generated by the detection of a transient at another waveband (i.e. a high-energy X-ray or gamma-ray transient). For example, X-ray observations by *Swift* of the abrupt end of the platau phase of some short-duration GRBs suggest evidence of the collapse of a supramassive neutron star [69] to a black-hole; the suggestion that such progenitors are linked with FRBs could be tested by this capability (3; 12). To allow such triggered follow ups, the provision of a large amount (ideally $>$100 PB) of temporary storage co-located with the telescope must be facili-

[66] In terms of electromagnetic radiation per unit solid angle.

[67] Similar to the VAST survey, CRAFT is commensal in that it will seamlessly tag on to a larger survey - in this case ASKAP.

[68] Telescope functions including pointing are performed by electronic manipulation of dipole signals

[69] A neutron star that is supported well above the maximum value allowed by its equation of state through centrifugal forces

tated.

ASKAP has the capability to scan the entire visible sky within 24 hours at sensitivities of 0.5 mJy or lower. This capability provides a fantastic opportunity to advance the study of known transients and variables and to discover new astrophysical objects and classes. VAST, a 1.4 GHz ASKAP Survey for Slow Variables and Transients, will exploit these capabilities focused to search for variables and transients with timescales as short as 5 seconds.

The Variables and Slow Transients[70] (VAST) survey will provide observations, complementary to a number of sources routinely observed at high energy (9). For example, the late time afterglow spectrum of a GRB will be observable at radio energies and the identification of a GRB 'orphan afterglows[71]' is a tantalising prospect. With a sufficient number of afterglows each year (10 or more), the prospects of constraining the beaming angles of GRBs, and thus, the true event rate would encouraging. However, recent studies based on the sample of *Swift* GRBs suggest that the sensitivity of ASKAP (~ 0.2mJy 1.4 GHz) may not be sufficient to achieve this science goal (6; 7); SKA2 (operational by 2015) however, would expected to detect radio afterglows for all bursts detected by a Swift type instrument (6). VAST could measure radio emission from a large number of XRBs which could be coupled with data from high-energy instruments such as *Swift* and *Fermi*. Such multi-wavelength observations could provide a new understanding of high-energy phenomena; for example correlated radio and X-ray observations of XRB systems can yield significant insight into the accretion-disk/jet coupling (4).

10.2.4 GRAVITATIONAL WAVES

The advanced network of interferometric gravitational wave detectors (Advanced LIGO, Advanced Virgo, and GEO-HF) will form a solid basis for the first detections with the first science run due in 2015 (see §8). Detector sensitivity is generally given by the detection range of the most likely expected events - the inspiral and merger of systems of binary neutron stars (BNSs). By 2017 (2019) this range will be sufficient to enable a detection range of 140 Mpc (200 Mpc), yielding up to 70 (200) BNSs a year. As BNSs have have been strongly postulated to be related to short duration γ-ray bursts, the electromagnetic follow-up of GWs candidates should become routine, firmly establishing the field of multimessenger astronomy. The possible simultaneous detection of any combination of photons, neutrinos or high energy particles with gravity waves from a gamma ray burst would be a landmark event for astrophysics. With the the worldwide network operating at design sensitivity, the accumulated numbers of detections will mean that GW astronomy will have entered the survey arena.

A LIGO-India Observatory running at aLIGO sensitivity will be added to the network by 2022 (at the time of writing - February 2014, this is subject to formal government approval) - at this time BNSs will be detectable out to 200 Mpc and of order 400 events will be expected

[70] `http://www.physics.usyd.edu.au/sifa/vast`

[71] An orphan afterglows can occur from a GRB whose jet not beamed in our direction

each year. An Indian detector will increase the resolution to allow at least 20% of sources to be detected within 5°.

Achieving good directional sensitivity would be of paramount importance for a scientific survey. For many sources, directional sensitivity is determined through triangulation of arrival times and the angular resolution of a GW network is inversely proportional to the separation of the detectors in the network. Thus, the addition of an Australian instrument and a Japanese observatory (a Japanese detector KAGRA, previously known as LCGT, could begin operation in 2018; 8) would increase the directional precision by a factor of 2.5 and the detection rate by a similar factor. Should the era of multi-messenger astronomy live up to its expectations, this scenario could become a distinct possibility in the forthcoming decade.

References

[1] de Naurois M., H.E.S.S. Collaboration 2013, Advances in Space Research, 51, 258

[2] Dubus G., Contreras J., Funk S., Gallant Y., Hassan T., Hinton J., Inoue Y., KnÃ¶dlseder J., Martin P., Mirabal N., de Naurois M., Renaud M., 2013, Astroparticle Physics, 43, 317

[3] Falcke H., Rezzolla L., 2013, arXiv:1307.1409

[4] Fender R. P., Belloni T. M., Gallo E., 2004, MNRAS, 355, 1105

[5] Gendre B., et al.„ 2011, Recent results of the FIGARO collaboration, http://sf2a.eu/semaine-sf2a/2010/proceedings/2010sf2a.conf..0167G.pdf

[6] Ghirlanda G., et al., 2013, MNRAS, 435, 2543

[7] Ghirlanda et al. 2014, PASA, under revision

[8] Kuroda K., the LCGT Collaboration 2010, Classical and Quantum Gravity, 27, 084004

[9] Murphy T., Chatterjee S., the VAST Collaboration, 2014, An ASKAP Survey for Variables and Slow Transients , http://www.physics.usyd.edu.au/sifa/vast/uploads/Main/vast_memo1.pdf

[10] Pillepich A., Porciani C., Reiprich T. H., 2012, MNRAS, 422, 44

[11] Thornton D., et al., 2013, Science, 341, 53

[12] Zhang B., 2014, ApJL, 780, L21

11 MULTI-MESSENGER ASTROPHYSICS

A key capability for observational studies of many of the sources of interest to this group is the ability to search the sky, or make follow-up observations, across the electromagnetic band. This capability arguably represents a “new wave” of astronomy, which capitalizes on the explosion of computing power and digitization of observing channels to (for example) carry out real-time, all-sky surveys at many wavelengths simultaneously for things that go “bump in the night". Australia is emerging as a priority site for a number of next-generation, all-sky instruments which will further change the way we observe the universe around us. Radio transient factories like ASKAP, Molonglo, and MWA operate in dramatically different ways from most contemporary radio telescopes, and consist of an array of relatively standard antennas coupled to a sophisticated computer hardware and software system enabling them to look simultaneously in many directions. At the same time, robotic optical telescopes like Skymapper and the Zadko telescope in Australia, and many others in the northern hemisphere are able to rapidly respond to triggers from conventional instruments but also (within the next decade) from gravitational wave detectors In the X-ray to gamma-ray band, NASA's Swift satellite and others provide near all-sky monitoring of the X-ray and gamma ray bursts.

In the 2020s we can expect that we will be monitoring the sky simultaneously across the electromagnetic spectrum as well as with neutrino and gravitational wave detectors. The future of astronomy will increasingly see the emergence of multi-band, wide-field capability which, when coupled with the worldwide gravitational interferometer network, will give us vast new quantities of information with which to understand the universe around us.

This capability is emergent, having benefited from collective progress in specific wavebands, as well as (in a broad sense) the increased computing power and digital storage available at a fraction of the cost in the past. However, it is likely that to support the kind of science investigations discussed in §10.1, this area can also benefit from a strategic review. In this section we present some of the science motivators for this multi-messenger approach, as well as presenting some band-specific discussions of current and future capabilities and how to ensure continuing Australian access to these resources.

11.1 RADIO/SUB-MM OBSERVATIONS

One of the key goals of the "New Horizons" Decadal Plan was for Australia to engage in the Square Kilometre Array (SKA) at the 10% level. This goal has been realised, with Western Australia selected to host both the low-frequency and the survey instruments of the SKA (SKA1-low and SKA1-survey). The final instrument to be constructed in Phase 1, SKA1-mid, will be located in South Africa. The telescopes hosted by Australia will build on the radio astronomy infrastructure that has been so successfully established in Western Australia over the past decade, not only at the telescope site at the Murchison Radio astronomy Observatory (MRO), but also including the fast data transport links and the supercomputing facility under construction at the Pawsey Centre in Perth. The low-frequency SKA precursor instrument, the Murchison Widefield Array (MWA), has recently completed its second semester of science observing, and the Australian SKA Pathfinder (ASKAP) is undergoing commissioning, with its first six phased array feed receivers (PAFs) installed on the six-antenna test array, BETA. Australian teams are heavily involved in many of the consortia responsible for SKA preconstruction work.

Fast radio bursts: These capabilities have enabled significant advances in the field of high energy and fundamental astrophysics. One of the most exciting developments in this area has been the detection of the so-called Fast Radio Bursts (FRBs); extremely bright, dispersed single radio pulses lasting just a few milliseconds in duration. First discovered in a reprocessing of the Parkes Multibeam Survey (19), the initial controversy over their extraterrestrial origin has been mitigated by the discovery of several more such bursts (36). Their high dispersion measures hint at an extragalactic origin, which, if confirmed, would allow a probe of the ionized intergalactic medium (26) (although for suggestions of a Galactic origin, see 18; 4). It is worthy of note that all except one (35) published burst detections to date are from the Parkes multibeam survey (19; 23; 36), whose combination of high sensitivity, large field of view and time on sky allow it to lead the world in this field.

Pulsars: Significant advances have also been made in pulsar research. Pulsar surveys such as the High Time Resolution Universe (24) have uncovered many exotic new pulsars, of interest from the perspectives of binary evolution (the "diamond planet (3); the link between pulsars and low-mass X-ray binaries (29); the millisecond pulsar in a triple system (31) or constraining the nuclear equation of state (the two-solar mass neutron star; (9). Pulsar timing at Parkes over a many-year baseline has placed the deepest constraints yet on the gravitational wave signal in the nHz range (33), and low-frequency radio observations have provided new insights into the pulsar emission mechanism (16; 15).

Jets and accretion physics: The detection of radio emission from a tidal disruption event (43) has uncovered a new class of radio transients and opened up a new approach to understanding the launching of relativistic jets. The recent discovery of HLX-1, a good candidate for an intermediate-mass black hole (10) has been followed up by a radio detection with the ATCA (40), showing that the coupling between accretion and ejection is invariant across the black hole mass scale. Multi-frequency observations, from the radio to the gamma-ray band have improved our understanding of accretion in both AGN (e.g. 2) and X-ray binaries, and detailed radio observations have begun to probe the jet launching region (14). Finally, new transient surveys have begun to place important limits on the rate of radio transients (see 12).

11.1.1 CURRENT RADIO INSTRUMENTS

As envisaged in "New Horizons", the ATNF has continued to facilitate the groundbreaking science being carried out at the Australia Telescope Compact Array (ATCA), the Parkes and Mopra radio telescopes, and the Australian Long Baseline Array (LBA). While some reprioritisation of funding has been necessary to support ASKAP and SKA-related activities, the capabilities of these existing national facilities have been considerably enhanced over the past decade. The installation of a new broadband backend at the ATCA has increased the sensitivity fourfold, enhanced the velocity resolution of the telescope, and significantly improved its survey speed and dynamic range. The incorporation of new stations to the LBA network (from WA to New Zealand), coupled with the increase in recording rates, has improved both sensitivity and imaging fidelity, and the advent of electronic Very Long Baseline Interferometry (e-VLBI), whereby data are transferred in real time over the internet, has enabled close to real-time imaging at the highest angular resolutions (e.g. 30).

11.1.2 FUTURE RADIO INSTRUMENTS

SKA and precursor facilities: The focus of much of the radio astronomy community over the coming decade will be the construction of the Square Kilometre Array (SKA). In phase 1, a low-frequency array (over 250,000 dipoles operating from 50-350 MHz) will be constructed in Western Australia. On the same site will be the 96-dish SKA1-survey array, operating from 650-1670 MHz, and using PAF technology to provide an 18-square degree field of view. Finally, in South Africa, SKA1-mid will consist of 254 dishes operating from 350 MHz to 3 GHz. Pre-construction activities are underway, with construction slated to begin in 2018, and early science from 2020.

Prior to the completion of SKA1, the large fields of view of the SKA pathfinders, MWA (600 square degrees; 37) and ASKAP (30 square degrees; 22) will usher in the era of radio sky monitors, complementing the capabilities of both the Low Frequency Array (LOFAR) in the north, and ongoing optical transient surveys (e.g. the Palomar Transients Factory) and X-ray all-sky monitors (Swift, MAXI, Fermi). MWA is already in full operations mode, with a field of view of up to 1000 square degrees and a confusion-limited sensitivity of a few mJy in Stokes I (which can be reached in just a few minutes). This is already enabling large-area surveys for transients (e.g. 5). In the next few years, the completion of ASKAP will provide further new opportunities for the field of high energy and fundamental astrophysics.

Pulsars and fast transients: Surveys for fast (sub-second) transients (e.g. CRAFT; 25) will unveil the nature of the enigmatic FRBs, probing fundamental physics in extreme states of matter and strong gravity. They will also detect new pulsars, searching for the exotic (fast, massive or binary) pulsars that can constrain the nuclear equation of state and test theories of strong gravity. Since accurate localisation is key to determining the true nature of FRBs, interferometers have a big advantage over the single-dish studies performed to date by Parkes and Arecibo. A commensal search on the VLBA (V-FASTR; 39) has pioneered an interferometric approach, but suffered from the small fields of view at GHz radio frequencies. Prior to the completion of SKA Phase 1, the wide field of view and large collecting area of the MWA provide one possible opportunity for FRB localisation, depending on the poorly-constrained source properties (38), as would the completion of the ongoing upgrade to the SKA Molonglo Prototype (SKAMP; Bailes, priv. comm.).

The next decade also holds the tantalising prospect of the detection of gravitational waves via Pulsar Timing Array experiments. While the sensitivity and long existing time baseline of Parkes observations have allowed the Australian team (the Parkes Pulsar Timing Array; PPTA) to develop a lead over its European and North American competitors, the three groups are now collaborating to more rapidly achieve a detection. Detection of new candidates for pulsar timing, or exotic pulsars, can be achieved by continued pulsar surveys, which can discover important systems for constraining the nuclear equation of state or binary evolution. The steep spectra of typical radio pulsars imply that the MWA and SKA-low will provide major new opportunities for pulsar surveys, as well as permitting detailed studies of the pulsar mechanism. These new instruments will be complemented by the proposed Parkes ultra-wideband (UWB) receiver, which is also vital for development of the precision pulsar timing projects at Parkes. New international instruments providing high sensitivity for pulsar timing and searching are the MeerKAT South African SKA Pathfinder and the Chinese 500-m diameter FAST radio telescope, both scheduled to begin operations in 2017. The MeerKAT South African SKA pathfinder will begin operations in 2017, and with its large gain, wide bandwidth and low system temperatures, will be the dominant pulsar timing facility until the completion of SKA1.

Slow transients: The wide field of view of ASKAP, and the high survey speed enabled by the PAF technology will allow a daily survey of 10,000 square degrees to detect slow radio transient events via imaging techniques, to a depth of 0.5 mJy/beam (28). Such transients are likely to be powered by either stellar explosions (gamma-ray bursts and supernovae) or accretion (such as tidal disruption events, active galactic nuclei, X-ray binaries, ultraluminous X-ray sources, or cataclysmic variables). Detailed monitoring and broadband follow up of such events can address important issues including the rate of massive star formation across cosmic time and the launching of relativistic jets. Key science projects to detect new transients have been approved on both ASKAP (VAST; 28) and MeerKAT (ThunderKAT), and transients form one of the main science areas for MWA (7).

VLBI: As the only southern hemisphere VLBI facility, the Australian LBA provides a key capability for transient follow up; imaging supernova expansion to determine the expansion velocity and geometry of the ejecta (e.g. 6). Resolving relativistic jets from X-ray binaries and AGN can probe the launching and propagation of the jets, and their subsequent interaction with their environments. Coupled with X-ray observations from satellites, this can probe the universal link between accretion and jet ejection (e.g. 27). VLBI is envisaged as a future capability of SKA, potentially by phasing up the core of SKA-mid (and potentially SKA-survey) to provide an extremely sensitive element that can be incorporated in existing VLBI networks such as the LBA. An array consisting of the current LBA and a phased-up SKA1-survey in Australia, plus Hartebeesthoek and a phased-up SKA1-mid in South Africa could reach an rms noise level of 1.5 microJy/beam in 2 hours of on-source time (assuming a bandwidth of 512 MHz), a factor of 15 better than current capabilities. This would enable VLBI studies of fainter objects, including the faint AGN population (to help distinguish starbursts from AGN activity), and extend existing VLBI studies of black hole X-ray binaries to their fainter neutron star and white dwarf analogues.

Adding the sensitivity of SKA as a tied array to existing VLBI networks would also enable extremely precise astrometry, at the few microarcsecond level, allowing the measurement of model-independent parallax distances and proper motions for objects anywhere in the Galaxy. Accurate distances and proper motions are critical when using precision pulsar timing to test theories of gravity. Strong-field gravity tests using the binary pulsar B1913+16 are currently limited by uncertainties in the differential acceleration of the Earth and the pulsar system toward the Galactic Centre (41), and for other double neutron-star systems uncertainties in their distance and proper motion are limiting factors. Further, by breaking the degeneracy between position uncertainty and pulsar spin-down, accurate astrometry can reduce the amount of observing time required to get a coherent pulsar timing solution, thereby assisting in the selection of pulsars for the Pulsar Timing Array. (34) review the potential of the SKA for pulsar astrometry, and (13) give a detailed overview of the full science case for VLBI with the SKA.

Cosmic rays: Existing or enhanced Australian radio facilities could also allow significant progress to be made in the field of high-energy cosmic rays over the next decade. A phased array feed on Parkes could detect broadband nanosecond-timescale pulses of Cerenkov radiation from the interaction of 10^{19} GeV cosmic rays with the lunar regolith (20), and it has been estimated that the low-frequency component of the SKA could detect such events at the rate of a few per day (21)). With appropriate access to the raw antenna voltages, MWA or SKA-low could also detect and study cosmic ray-induced atmospheric air showers, as already done with LOFAR (32).

International facilities: World-class radio facilities are not just being built and operated in Australia, but across the globe. The expertise of Australian astronomers has led to their being awarded significant amounts of observing time in competitive proposal rounds for time on open skies international facilities. The recent sensitivity upgrade to the Karl G. Jansky Very Large Array (VLA) has allowed it to reach sub-microJansky sensitivity, making it the world's most sensitive operational radio telescope. Other key radio facilities with open skies policies include the Very Long Baseline Array and the Green Bank Telescope, both also run by NRAO at present, but facing an uncertain future following the recommendations of the NSF's Portfolio Review Committee. The Atacama Large Millimeter/submillimeter Array[72] (ALMA) has commenced operations, providing the world's largest and most sensitive mm-frequency interferometer. Although Australia made a decision not to join the ALMA partnership, Australian astronomers may nonetheless apply for "Open Skies" time. Over the next decade, the Event Horizon Telescope collaboration will enable ALMA to be phased up and added to a sub-millimetre VLBI array in order to directly image the shadow of the event horizon in the nearby supermassive black holes, Sgr A* and M87 (see (11) for more details and other applications).

In Europe, e-MERLIN is now operational, providing sensitive medium-resolution imaging, down to noise levels of a few microJy/beam, on scales of a few tens to hundreds of milliarcseconds. The European VLBI Network has also increased its available bandwidth over the past

[72] http://www.almaobservatory.org

decade, and has introduced regular e-VLBI sessions for the study of transient phenomena. The recently-operational Low Frequency Array (LOFAR) in the Netherlands and across Europe provides complementary coverage to MWA for the northern sky, albeit at significantly higher angular resolution. And the Westerbork Synthesis Radio Telescope (WSRT) is being revitalised with focal plane array technology, with the Apertif system increasing its field of view by a factor of 25.

Finally, in Asia, the Giant Metrewave Radio Telescope (GMRT) provides coverage from 50 MHz to 1.4 GHz, with a frequency-dependent angular resolution of 2-60”, and a sensitivity of tens to hundreds of microJy per beam. There are small VLBI networks in China (CVN) and Japan (VERA), focussing primarily on astrometry. The Korean VLBI Network (KVN) provides some millimetre-wavelength VLBI capability. Finally, the construction of FAST, the Five hundred metre Aperture Spherical Telescope, has now begun in China. With three times the sensitivity of Arecibo, FAST will be the world’s largest single dish telescope, operating from 0.1–3 GHz and able to observe within 40 degrees of the zenith.

11.1.3 THE FUTURE OF RADIO ASTRONOMY

As many of the existing or upcoming facilities have Open Skies policies, at least at some level, no additional investment is required to take advantage of them, other than fostering scientific excellence. However, it is critical for Australia to maintain its leading role in the SKA, which will not have an Open Skies policy, but will be the major radio/sub-millimetre investment over the next decade. One issue of concern is the possibility of a change to NRAO’s Open Skies policy. Should this come about, it will be essential for ATNF and the SKA Organisation to work with NRAO on a reciprocal access agreement, to ensure that Australian astronomers do not lose access to NRAO’s suite of world-class facilities. Even in the era of SKA, the VLA will remain the most sensitive radio facility on the planet above the highest possible SKA frequency of 14 GHz.

The huge data volumes generated by the new instruments (MWA, ASKAP and phase 1 of the SKA, but also the new broadband receivers on the Compact Array and the VLA) place significant demands not only on compute power and storage space, but also on manpower to reduce and analyse the data. Transient work also requires rapid turnaround, to be able to follow up any newly-detected events and send out triggers to both the internal and external communities, thereby optimising the science return. The availability of ARC schemes to provide the necessary manpower will be critical to ensure the success of these transients programs.

With the wide fields of view available from ASKAP, MWA, SKA1-low and SKA1-survey, commensal observations can maximise the scientific return of any observing time, increasing the opportunity for transient detection by an order of magnitude or more relative to dedicated transient search time. Appropriate spigots to access the data streams and pipelines to automatically and rapidly process the data will be needed, as will a mechanism such as VOEvent for communicating to the wider community the anticipated large number of transient alerts generated.

Finally, follow up of newly-detected transient events at higher frequency and higher angular resolution than possible with the wide-field radio instruments coming online over the next decade (e.g. MWA, ASKAP, SKA1-survey) will be crucial to establish their nature and the underlying physics. While this necessarily implies co-ordination with multi-wavelength facilities (e.g. optical imaging to provide host galaxy redshifts, X-ray satellites to search for accretion signatures), Australia should also leverage its existing suite of world-class facilities – for instance by following up newly-detected ASKAP transients at higher frequency with the ATCA and at higher angular resolution with the LBA. However, current budgetary constraints are placing many of Australia's workhorse radio facilities (Parkes, ATCA, LBA, Mopra) under stress, threatening some of the current capabilities. Continued operational funding is needed to head off such a scenario. Furthermore, the continued operation of Parkes for pulsar timing studies is one of the highest priorities for radio and sub-mm observations in the field of high-energy and fundamental astrophysics.

11.2 OPTICAL/IR OBSERVATIONS

A key feature of accreting compact objects (including but not limited to quasars and microquasars) is that they release a lot of energy into the surrounding environment. In some cases, this has strong effects on the structure and evolution of the host galaxy, of its interstellar medium and of the hot gas in galaxy clusters. Spectroscopic studies of the region around a black hole is the key to determine plasma properties and stellar dynamics, and ultimately the effect that black hole power (high-energy photons and jets) has on its environment. Therefore, this area of research naturally aligns with key science drivers for the SKA.

The most important requirements for a productive synergy between optical observations and those in other bands, are:

- coordination with detection and monitoring of high-energy transients (e.g. discovered by *Swift* and MAXI): requires new, fast-slewing 1m- or 2m-class telescopes built in Australia; also, retain or expand ToO programs on the AAT;
- complementarity with high-resolution imaging studies of X-ray sources in nearby galaxies: requires optical sub-arcsec resolution (matching *Chandra*'s spatial resolution) and 8-m class telescopes;
- cooperation with high-resolution spectroscopic studies of X-ray emitting gas, inflows and outflows in galaxies and clusters: integral field units on the AAT and the Giant Magellan Telescope.

For gravitational wave studies, the ideal optical support at this stage are new Australian telescopes in the 0.5 m to 1 m class, with a very large field of view (several square degrees) and fast slewing. Such instruments will also broadly support general transient detection and followup programs (see §10). Below we discuss the current capabilities and likely future opportunities and requirements in more detail.

11.2.1 CURRENT OPTICAL INSTRUMENTS

The 4-m Anglo-Australian Telescope[73] (AAT) has served as the national work-horse for cutting-edge areas of research related to high-energy astrophysics (in addition to improving its target-of-opportunity observation scheme, as discussed above).

The AAT has already pioneered Integral Field Unit (IFU) spectroscopy with SPIRAL, and multi-IFU spectroscopy with SAMI (Sydney-AAO Multi-object Integral-field-spectrograph). Concept studies are under way at the AAO for the design of a new instrument (HECTOR), which will use an automated robotic system for the deployment of fibre hexabundles to the focal plane. Although designed for optical galaxy surveys, IFU instruments at the AAT provide important contributions to research in the high-energy field. For example, such instruments enable studies of galactic dynamics aimed at estimating their nuclear black holes masses, which can be combined with SKA-based radio and space-based X-ray studies of their accretion power, leading to a greater understanding of black hole growth and of the physics of accretion.

In the field of X-ray spectroscopy, the Japanese satellite *Astro-H* (scheduled for launch in 2015) will provide significant progress thanks to its revolutionary calorimeter spectrometer. In contrast to a grating, the spectral resolution of the calorimeter is unaffected by source size because it is non-dispersive; thus, *Astro-H*'s Soft X-ray Spectrometer will enable high-resolution spectroscopy of extended sources, revealing for example line broadening and Doppler shifts due to turbulent or bulk velocities of starburst and AGN outflows. Other areas which will be greatly enhanced by the new spectroscopic capability are the identification of galaxy cluster mergers, the mapping of kinematics and metal abundance of ejecta in supernova remnants, the study of abundance gradients in clusters and elliptical galaxies. In most of those fields, it will be very useful to carry out parallel investigations with integral field spectrographs in the optical band. For example, only a combination of X-ray and optical spectroscopy of extended starburst superwinds will enable us to model the temperature, velocity and density structure of the multiphase gas. In all those cases, the AAT's IFU capability will be in high demand, and Australian astronomers are already at the forefront also of the theoretical modelling of such systems.

11.2.2 FUTURE OPTICAL INSTRUMENTS

In-depth studies of the optical counterparts is a key requirement of most research in high-energy sources (both thransient and persistent). For accretion onto stellar and (if they exist) intermediate-mass black holes, a rule of thumb is that the X-ray flux is ~ 100–1000 times higher

[73] `http://www.aao.gov.au/about-us/anglo-australian-telescope`

than the optical flux. That means that 8-m class telescopes are usually required for in-depth optical studies even of accreting sources that appear relatively bright in X-ray telescopes such as *Chandra* and *XMM-Newton*. To use a specific example: in the past decade, the increased spatial resolution and sensitivity of space-based high-energy detectors has allowed ground-breaking discoveries of different types of accreting black holes in nearby galaxies, whereas until the 1990s, our knowledge of non-nuclear black holes was mostly limited to those in the Milky Way environment. Over the next decade, the search for microquasars and intermediate-mass black holes will be extended to distances ~ 100 Mpc. Most of this research can only be done with subarsec optical resolution, ideally with *HST* and *JWST* (the former, and hopefully also the latter, very successfully used by Australian astronomers through competitive time allocation processes) but also with 8-m-class telescopes with adaptive optics (especially for spectroscopic observations of targets identified with *HST*).

The strongest recommendation for optical astronomy in the 2006–2015 Decadal Plan and in its Mid-Term Review was that in the period 2013–2015, Australia must secure access to at least 20 per cent of an 8-m telescope. In 2013, Australia had a nominal 6.66 per cent share of each Gemini telescope, corresponding to 13 per cent of an 8-m telescope; the over-subscription ratio for Australian astronomers is only around 2 (in line with the ratio for the other partners of the Gemini consortium; http://www.gemini.edu/node/10771?q=node/11676), which makes it objectively hard to argue for much increased Australian investment in Gemini. In addition, Astronomy Australia Limited (AAL) has secured funds from the Federal government's Collaborative Research Infrastructure Scheme (CRIS) and National Collaborative Research Infrastructure Strategy (NCRIS) to purchase access to 15 nights a year on the twin 6.5m Magellan telescopes (at Las Campanas, Chile); in 2014, the Carnegie Institution for Science and AAL have extended this agreement until Semester 2017B. This successful agreement is consistent with the higher demand (mean over-subscription since 2007 ≈ 3.5) by Australian astronomers to use the Magellan telescopes. Including these nights into the 8-m class share gives a total of 17 per cent of an 8-m telescope, still below the target. On the other hand, suitable collaborative strategies with US or European co-authors have given Australian astronomers additional access to 8-m-class telescopes: a random scan of recent X-ray/optical studies led by Australian-based researchers shows extensive use of ESO telescopes (VLT and NTT) as well as Magellan time not included in the Australian share. Moreover, Swinburne University has access to 15 nights a year on the 10-m Keck (Hawaii).

In summary, access to an equivalent 8-m telescope is now roughly at the 20 per cent level advocated by the Decadal Plan. Discussion of the future investment strategies (increase in the Gemini share? Focus investments on the Giant Magellan Telescope? Join ESO?) is beyond the scope of this high-energy review. However, a very informal survey of a random (and limited) sample of Australian astronomers involved in X-ray/optical studies suggests a preference for an ESO strategy. This was also mentioned in the Mid Term Review of the 2006–2015 Decadal plan: "Australia should pursue membership in ESO to gain access to a number of advantages including: a wider spectrum of 8-metre telescopes and instrumentation, ALMA, and secure involvement in the E-ELT. At the present time, it is unclear which of the world's three ELTs will reach completion, but involvement in both GMT and the European ELT spreads that risk. Partnership with ESO will also ensure that Australia has the portfolio of infrastructure to support its ambitions for the SKA, both now, and into the future." (page 18). And: "The astronomy community's clear preference is ESO membership, but we recognise that funding for this is unlikely to be available before 2015 and so both options should be pursued in the short term." (page 44).

However, this is by no means a unanimous view: a number of other Australian astronomers have expressed (publicly but more often privately) motivated opinions about why ESO membership would be a bad investment of money, except perhaps for the few institutions that can benefit from building instruments for ESO, most notably the ANU. A likely drawback of the expensive ESO membership are cuts to several successful but smaller-scale projects and facilities, with great damage to the diversity of Australian astronomy. A third (more zen-like) approach to the ESO question is that it is not worth wasting much time debating pros and cons of this hypothetical situation because it is outside the realm of physical possibilities for any foreseeable future: there is simply not enough taxpayers money available to build the SKA, support the diversity of successful Australian research (including gravitational wave projects), *and* commit to paying at least $10 million of ESO membership fees each year for an unlimited number of years.

11.3 X-RAY ASTRONOMY

In the past, the Australian community has had no formal role in a major X-ray astronomy space mission. However, the international space science community, notably NASA and ESA, have generally provided guest observer programmes open to all, giving Australian astronomers access to observing time on major X-ray satellites. Satellite data are also generally made public after a proprietary period that is one year for NASA missions. Public X-ray data can be accessed readily in the NASA HEASARC archive.

Since the 2006 Decadal Plan, groups working in observational X-ray astronomy have been established at the University of Sydney, led by Bryan Gaensler, at Monash University, led by Duncan Galloway and at Curtin University, with James Miller-Jones and Roberto Soria. These groups represent a major step up in the level of expertise in observational X-ray astronomy in Australia. As multiwavelength astronomy has gained in importance, they represent a valuable new resource for the Australian community.

No new high resolution imaging X-ray astronomy missions are planned for the next decade. The *Chandra* and *XMM-Newton* satellites, which have been the workhorses of X-ray observations since their launches in 1999, are both ageing. The earliest proposed launch date for a comparable or better X-ray mission, the ESA Athena mission (44), is in 2028, beyond the end of the review decade. The future is more positive for X-ray surveys and spectroscopy of brighter

X-ray sources, as outlined below.

11.3.1 SYNERGY WITH RADIO ASTRONOMY

Many high energy phenomena are more readily observed in the radio and X-ray than at intervening wavelengths. This creates a synergy between radio and X-ray observations that the Australian community should exploit to maximise the scientific return as new radio facilities are developed here. For example, a single population of relativistic electrons may produce synchrotron radiation from the radio through to the X-ray, in which case observations in both wavelength ranges best constrain the electron energy distribution and acceleration mechanisms. Electrons producing radio synchrotron emission typically Compton scatter photons from the cosmic microwave background and other sources into the X-ray band. Combining radio and X-ray observations can then determine the magnetic field strength and other key properties of a source. The parameters of shocks in supernova remnants and in merging galaxy clusters can be determined from thermal X-ray emission and related to the population of relativistic electrons accelerated by the shock that is probed by its radio emission.

11.3.2 CURRENT X-RAY MISSIONS

Among current X-ray missions, *Chandra* (53) and *XMM-Newton* (48) provide the greatest capabilities for X-ray observations in the 0.3 – 10 keV range. *Chandra* has better spatial resolution, at $\simeq 1''$, while *XMM-Newton* has greater effective area, notably at higher X-ray energies. Both satellites have CCD detectors at the focus of X-ray telescopes for imaging spectroscopy, as well as gratings to provide higher spectral resolution. The *Suzaku* mission (51) also has an X-ray telescope with CCD detectors with comparable effective area to *Chandra*. It has poorer spatial resolution ($\simeq 1'$), but its low internal background and moderately better energy resolution give it an edge for obtaining spectra of faint extended X-ray sources. *Suzaku* also has a non-imaging, 10 – 600 keV X-ray detector. Recent problems due to degradation of its batteries suggest that it is nearing the end of its life. Other high energy satellites include lower resolution or non-imaging, hard X-ray detectors. For example, the *Swift* mission includes the 15 – 150 keV coded mask Burst Alert Telescope, with a 2 steradian field of view and CZT detectors, as well as an 0.2 – 10 keV Wolter I telescope with CCD detectors. While its main purpose was to study gamma-ray bursts (46), it has also proved useful for observing X-ray transients and bright, variable X-ray sources (17; 8), as well as more general X-ray observations. The recent NASA Senior Review has recommended *Swift* funding continue until 2018 and the satellite is expected to function until beyond 2025. Perhaps the most significant recent X-ray mission is *NuSTAR*, which was launched in June 2012 (47). Its hard X-ray telescope provides imaging spectroscopy in the energy range 3 – 80 keV, with a spatial resolution of $\simeq 1'$, dramatically improving sensitivity in this energy range over previous X-ray missions.

11.3.3 FUTURE MISSIONS

Noteworthy X-ray missions to be launched in the coming decade include the Japanese *Astro H* satellite, which is scheduled for launch in 2015 (52). It will have an array of X-ray calorimeters, with 7 eV energy resolution in the energy range 0.3 – 12 keV, at the focus of an X-ray telescope, providing imaging spectroscopy with at least an order of magnitude better energy resolution than any previous instrument. *Astro H* will also includes a hard X-ray telescope with comparable performance to *NuSTAR*, a soft X-ray telescope and a non-imaging detector for the energy range 10 – 600 keV. The second significant X-ray mission, with a planned launch date in 2016, is the Russian-German *Spektrum-Roentgen-Gamma*. Its payload includes soft and hard X-ray telescopes to be used for an all-sky X-ray survey. The primary instrument is the soft X-ray telescope, *eROSITA*, which will produce an X-ray catalogue with ~ 20 times the depth of the *ROSAT* catalogue (49). It is very significant that CAASTRO has signed a Memorandum of Understanding allowing its members access to *eROSITA* data for projects that require combining their data with *eROSITA* X-ray data. Potentially, this will be a valuable resource for the Australian community. It also provides a model for using Australian resources to leverage access to international facilities, including forthcoming X-ray missions, going into the future. The Indian *ASTROSAT* mission is due for launch in 2015 and has a planned lifetime of 5 years. It will carry four X-ray instruments, an 0.3 – 8 keV X-ray telescope, a large area of collimated proportional counters for the 3 – 100 keV range, a 10 – 100 keV CZT array with coded mask imager and a 2 – 10 keV scanning sky monitor. Its payload is well suited to the interests of X-ray astronomers in Australia.

There will be other, more specialised, X-ray missions, in the coming decade. At present, the Neutron Star Interior Composition Explorer (*NICER*) is scheduled for launch in 2016 and may have a guest observer program. It will carry a non-imaging 0.2 – 12 keV detector with a large effective area, a time resolution of 300 ns and an energy resolution of order 100 eV.

11.3.4 THE FUTURE OF X-RAY ASTRONOMY

The heavy investment in radio astronomy by Australia implies a strong, continuing commitment to research in high energy astrophysics. To fully exploit the opportunities this presents will require an appreciable level of expertise in observational X-ray astronomy. Although the necessary expertise can be accessed through international collaboration, the research would be more efficient and the return to Australian science greater through local collaboration. The open MoU between CAASTRO and *eROSITA* illustrates the issue. Australian researchers would be much better placed to exploit this opportunity if they had ready access to local expertise for informal discussions of what may be achieved using *eROSITA* data. To this end, the community should endeavour, at least, to maintain the current level of expertise in this field.

Fortunately, members of the Australian community continue to be given access to major X-ray observatories and their data free of charge. In the past, funds have been set aside to support Australian astronomers to visit overseas institutions, enabling them to consult with experts when collecting new satellite data. Although the increase in local X-ray astronomy expertise has reduced the need for this, there will still be occasions that demand it. Even for experts, it takes time to become familiar with a new mission and this is done most efficiently in close consultation with the people who developed and operate it. Also, it is often most efficient for people new to a field, notably students, to be able to consult a wide range of experts when they are learning how to exploit unfamiliar data. Continuing to provide funds for "satellite" observing trips would help to maximise the exploitation of X-ray data.

References

[1] Ott, C. D. et al. (2013) PRD, 86, 024026

[2] Acciari, V. A., et al., 2009 , Science, 325, 444

[3] Bailes, M., et al., 2011 , Science, 333, 1717

[4] Bannister, K. W., & Madsen, G. J., 2014 , arXiv:1402.0268

[5] Bell, M., et al., 2014 , MNRAS, 438, 352

[6] Bietenholz, M. F., 2014 , PASA, 31, 2

[7] Bowman, J. D., et al., 2013 , PASA, 30, 31

[8] Curran, P. A., et al., 2011, MNRAS, 410, 541

[9] Demorest, P. B., Pennucci, T., Ransom, S. M., Roberts, M. S. E., & Hessels, J. W. T., 2010, Nature, 467, 1081

[10] Farrell, S. A., et al., 2009 , Nature, 460, 73

[11] Fish, V., et al., 2013 , arXiv:1309.3519

[12] Frail, D. A., Kulkarni, S. R., Ofek, E. O., Bower, G. C., & Nakar, E., 2012 , ApJ, 747, 70

[13] Godfrey, L. E. H., et al., 2012 , PASA, 29, 42

[14] Hada, K., Doi, A., Kino, M., Nagai, H., Hagiwara, Y., & Kawaguchi, N., 2012 , Nature, 477, 185

[15] Hassall, T. E., et al., 2013 , A&A, 552, A61

[16] Hermsen, W., et al., 2013 , Science, 339, 436

[17] Krimm, H. A., et al., 2007, ApJ, 668, 147

[18] Loeb, A., Shvartzald, Y., & Maoz, D., 2014 , MNRAS, accepted

[19] Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J. & Crawford, F., 2007 , Science, 318, 777

[20] James, C. W., et al., 2013 , ICRC Conference Proceedings

[21] James, C. W., & Protheroe, R. J., 2009 , Astroparticle Physics, 30, 318

[22] Johnston, S., et al., 2007 , PASA, 24, 174

[23] Keane, E. F., Stappers, B. W., Kramer, M., & Lyne, A. G., 2012 , MNRAS, 425, L71

[24] Keith, M. J., et al., 2010 , MNRAS, 409, 619

[25] Macquart, J.-P., et al., 2010 , PASA, 27, 272

[26] Macquart, J.-P., & Koay, J. Y., 2013 , ApJ, 776, 125

[27] Miller-Jones, J. C. A., et al., 2012 , MNRAS, 421, 468

[28] Murphy, T., et al., 2013 , PASA, 30, 6

[29] Papitto, A., et al., 2013 , Nature, 501, 51

[30] Phillips, C. J., et al., 2007 , MNRAS, 380, L11

[31] Ransom, S. M., et al., 2014 , Nature, 505, 520

[32] Schellart, P., et al., 2013 , A&A, 560, 98

[33] Shannon, R. M., et al., 2013 , Science, 342, 334

[34] Smits, R., Tingay, S. J., Wex, N., Kramer, M., & Stappers, B., 2011 , A&A, 528, A108

[35] Spitler, L. G., et al., 2014, ApJ, submitted (arXiv:1404.2934)

[36] Thornton, D. et al., 2013 , Science, 341, 53

[37] Tingay, S. J. et al., 2013 , PASA, 30, 7

[38] Trott, C. M., Tingay, S. J., & Wayth, R. B., 2013 , ApJ, 776, L16

[39] Wayth, R. B., Brisken, W. F., Deller, A. T., Majid, W. A., Thompson, D. R., Tingay, S. J. & Wagstaff, K. L., 2011 , ApJ, 735, 97

[40] Webb, N., et al., 2012 , Science, 337, 554

[41] Weisberg J. M., Nice D. & Taylor J. 2010, ApJ, 722, 1030

[42] Anderson, S. B., & Jenet, F. A., 2008 , ApJ, 674, 286

[43] Zauderer, B. A., et al., 2011 , Nature, 476, 425

[44] Barret D, Nandra K, Barcons X, Fabian A, den Herder JW, Piro L, *et al.*, 2013, in L Cambresy, F Martins, E Nuss, A Palacios, eds., *SF2A-2013: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics*, pp. 447–453

[45] Fabian AC, 2012, *ARA&A*, **50**, 455

[46] Gehrels N, Chincarini G, Giommi P, Mason KO, Nousek JA, Wells AA, *et al.*, 2004, *ApJ*, **611**, 1005

[47] Harrison FA, Craig WW, Christensen FE, Hailey CJ, Zhang WW, Boggs SE, *et al.*, 2013, *ApJ*, **770**, 103

[48] Jansen F, Lumb D, Altieri B, Clavel J, Ehle M, Erd C, *et al.*, 2001, *A&A*, **365**, L1

[49] Merloni A, Predehl P, Becker W, Böhringer H, Boller T, Brunner H, *et al.*, 2012, *arXiv:1209.3114*

[50] Miller-Jones JCA, Sivakoff GR, Altamirano D, Coriat M, Corbel S, Dhawan V, *et al.*, 2012, *MNRAS*, **421**, 468

[51] Mitsuda K, Bautz M, Inoue H, Kelley RL, Koyama K, Kunieda H, *et al.*, 2007, *PASJ*, **59**, 1

[52] Takahashi T, Mitsuda K, Kelley R, Aharonian F, Akimoto F, Allen S, *et al.*, 2010, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, volume 7732 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*

[53] Weisskopf MC, Brinkman B, Canizares C, Garmire G, Murray S, Van Speybroeck LP, 2002, *PASP*, **114**, 1

A GRAVITATIONAL WAVE ASTROPHYSICS

This section contains an abridged version of the scientific opportunities that the next decade will present in gravitational wave science. More details can be found in the US Astro2010 Decadal Survey[74] and the GWIC roadmap[75].

A.1 NEW PHYSICS: TESTING EINSTEIN'S THEORY

The successful detection of gravitational waves will mark the start of a major line of discovery focused on the testing of the General Theory of Relativity. In the solar system, the predictions of General Relativity are so subtly different from Newton's theory that it takes extremely precise measurements to observe differences between the two. Thus the solar system tests of General Relativity can be characterized as high precision measurements in the weak-field limit. Even today, after almost a century of experiments, the precision of testing the crucial "magnetic" component of the gravitational force is no better than about 10% (1) The difficulty arises because gravity in the solar system is extremely weak; gravitationally induced velocities (such as orbital speeds) are very small compared to the speed of light.

Moreover, all of the solar system tests are in the static regime – the equivalent of testing electromagnetism through electrostatics and magnetostatics only. Such a test, without any observations of electromagnetic waves, would be a very limited confirmation of the full Maxwell Equations. The dynamic aspects of General Relativity have only been tested through the observation of the binary pulsars. By monitoring one remarkable system over years, Joseph Taylor and Russell Hulse were able to demonstrate that the energy loss in the system matched the prediction of Einstein's theory for the energy radiated in gravitational waves. This result was recognized by the Nobel Prize in 1993.

In Einstein's theory, gravitational waves travel at the speed of light and have two polarization states. In alternative theories, other possibilities exist, for example if gravitons (carriers of the gravitational force, analogous to photons) have a non-zero rest mass due to the presence of a scalar field. Solar system tests currently lack the precision to discriminate between these alternatives. Gravitational wave detectors will provide new and decisive tests of this theory. Comparisons of the arrival time of electromagnetic waves and gravitational waves from the same object will give a precise test of the speed of travel of gravitational waves. Comparisons of the signals in detectors of different orientations can give information about the polarization states (2).

[74] http://sites.nationalacademies.org/bpa/BPA_049810
[75] https://gwic.ligo.org/roadmap

Unlike Maxwell's equations, Einstein's field equations are inherently non-linear, and thus exotic new phenomena are expected in the strong field limit, i.e., when space-time is strongly curved. Black holes are the extreme manifestation of this nonlinearity, and gravitational waves from black holes can also be used for strong field tests of General Relativity. The most promising systems for such tests are coalescing binary black holes (3). The Advanced LIGO detectors are expected to observe at least a few black hole coalescence events per year, and possibly many more. The signal from such a coalescence is a rising tone that sweeps upwards across the detection band over a period of minutes (a "chirp"), with modulations in intensity determined by the spin of the individual black holes. When the holes merge, the decaying ringtone of the newborn hole provides a precise description of the black hole mass and angular momentum. A major break-through in the past few years has come from applying modern super-computers to solve Einstein's equations numerically to produce predictions for the gravitational waveforms from such systems (4). Comparing observed and predicted waveforms may give a precise confirmation that general relativity is correct, but could show deviations if new physics comes into play.

A.2 BLACK HOLE PHENOMENA

General Relativity predicts numerous properties of black holes which were "discovered" theoretically in the 1960s to 1980s by Penrose, Hawking, Thorne, Chandrasekhar, Wheeler and others. These "discoveries" are predictions and consequences of the General Theory of Relativity. Hawking's surface area theorem states that in all processes the black hole horizon area always increases. Wheeler coined the 'No Hair Theorem' to emphasise that black holes have only three observational properties, mass, charge and angular momentum, with a structure defined by an exact solution of the Einstein equation due to Kerr and Newman. Following from this is the famous black hole quantum information paradox that addresses the question of what happens to information when matter falls into a black hole. Chandrasekhar showed that black holes should have a spectrum of vibrational modes that depend uniquely on their mass and spin. Penrose introduced the 'Cosmic Censorship Conjecture' which says that the singularity inside a black hole is always hidden from the outside universe.

All of the above fundamental propositions, predictions and conjectures are amenable to observational testing by observing gravitational waves emitted during the formation and coalescence of black holes. The ringing of black hole normal modes tests General Relativity at the strongest fields. Measurements of the initial and final black hole masses test the surface area theorem. Systems with large mass ratios (e.g. where a smaller black hole coalesces with a larger one) test the no hair conjecture. A smooth transition from the chirp of the inspiral phase to the ringing normal mode of the final black hole will confirm aspects of general relativity, whereas departures would reveal new physics or violation of the cosmic censorship hypothesis.

An exciting possibility is the detection of gravitational wave "memory" from black-hole coalescences by Pulsar Timing Arrays (5; 6) This effect is predicted by General Relativity but has not yet been detected in any experiment. It contributes an increasing fraction of the total signal-to-noise ratio, as the redshift of the source increases.

A.3 NEUTRON STAR MERGERS

The Advanced LIGO, Virgo, and KAGRA detectors are designed specifically to search for coalescing binary neutron stars because progenitors for such events are known in the Milky Way and observational data allow lower limits to be set on their event rate. The current LIGO detectors measure their performance by the detectability range for neutron star coalescence. They have achieved a range of $\sim$200 Mpc. Advanced detectors are designed to increase this range 10-fold increasing the volume of space being monitored by a factor of 1000.

The neutron star coalescence signal can be well modelled in General Relativity up to the final few cycles, when tidal distortion becomes large. The characteristic chirp signal, which lasts for more than a minute, is distinctive. It can be extracted efficiently from noisy data by matched filtering. Best estimates predict about 50 detectable coalescence events per year (7). These systems are likely to be strong electromagnetic sources and it will be important to obtain prompt follow-up (a) to compare the velocity of gravitational waves with electromagnetic waves and (b) to fully understand the source.

A.4 NEW PHYSICS: UNDERSTANDING NUCLEAR MATTER

The theory of quantum chromo-dynamics (QCD) unifies the strong nuclear force (and its associated quarks and colour-charge carriers called gluons) with the weak nuclear force and electromagnetism. QCD has been tested successfully in the largest particle accelerators on Earth. However, accelerators only probe the simplest QCD reactions: pairs of particles colliding at high (TeV) energies. They cannot probe the fascinating collective phenomena which arise when multiple particles interact via QCD, as they do inside an atomic nucleus. Indeed, there is no way to study collective QCD experimentally on Earth in systems larger than a few hundred particles, because to do so would require compressing matter to 10^{17} times the density of water.

Gravitational wave observations can investigate this regime by probing the interiors of neutron stars, where matter exceeds nuclear density, and the physics is dominated by QCD. X-ray satellite measurements of spinning neutron stars in accreting binary systems offer indirect evidence that such objects emit persistent, periodic gravitational waves, generated by "mountains" on the solid surface of the star (8). Scorpius X-1, the brightest X-ray source in the sky, is a prime LIGO target (e.g. 9). Detecting gravitational waves from an object like Scorpius X-1 will constrain the elasticity and breaking strain of nuclear matter in its crystalline state as well as its composition. If the mountain arises from nuclear reactions or magnetic funnelling, the thermal conductivity and electrical resistance of nuclear matter can also be inferred. By analysing tidal signatures in the gravitational wave signal from coalescing neutron stars, one can also measure the pressure in nuclear matter as a function of density (the equation of state) to $\sim 10\%$ accuracy, while independently measuring fundamental quantities like the radius of the neutron to unprecedented accuracy (10)

Rotational glitches in isolated neutron stars are another promising gravitational wave source. Phenomenological theories predict that the signal from a glitch is of hybrid character, generated by disparate fluid motions within the star. Detecting gravitational waves from glitches could provide the first direct proof that bulk nuclear matter is a quantum fluid, as implied by studies of atomic nuclei. From the polarization and spectrum of the signal, the compressibility and viscosity of many-body nuclear matter can be extracted (11). These results can be linked to measurements of heavy ions in relativistic heavy-ion colliders such as the US Brookhaven National Laboratory. Such studies will enable stringent new tests of QCD, including its prediction of new states of matter like color-flavor locked and two-color superconductors (12).

A.5 NEW ASTROPHYSICS: COSMOLOGY WITH GRAVITATIONAL WAVES

Modern cosmology predicts that in its first fractions of a second the Universe underwent phase transitions, when the structure of spacetime changed suddenly, akin to the change from liquid water to solid ice. Gravitational waves offer the only direct means of observing this period. Fundamental theories predict that the phase transitions are accompanied by gravitational wave emission. Various scenarios predict different spectral signatures. Detection of these primordial signals would represent one of the most exciting discoveries in cosmology, providing a direct observational tool for understanding the big bang.

Gravitational waves also provide a powerful tool for probing the distributions of matter and energy in the universe. Modern astronomical observations imply that dark energy contributes about 73% of the total mass-energy of the universe, while dark matter contributes about 23%. One effective way to probe the nature and distribution of these dark components is to make precise measurements of the distance and the recession velocity (redshift) of distant galaxies. Currently supernovae are the only "standard candle" that allow such measurements. However gravitational wave signals from coalescing neutron stars or black holes provide an alternative, independent tool (13). This is possible because of the remarkable fact that gravitational wave signals from binary coalescence actually directly encode the distance of the source. This occurs because the relative polarisation amplitudes allow the normally undetectable orientation of a binary star system to be directly determined. By measuring the gravitational waveform, one can infer the parameters of the system (the masses and spins of the stars) and accurately deduce the distance.

The major advantage of coalescing binary black holes or neutron stars is that they eliminate the need to build a cosmic "distance ladder" for estimating cosmological distances. The signals are free from systematic errors such as dust obscuration, thus providing a completely independent verification of one of the most perplexing observations in modern cosmology.

To be able to achieve the above measurements it is essential to be able to identify the host galaxy in which a coalescence event occurs, so as to measure its redshift. Much theoretical work is still needed to determine the best way to do this, especially in the case of binary black hole coalescences, where the electromagnetic signature is likely to arise from the interaction of associated components like magnetized accretion disks (14; 15; 16). Cosmological experiments of this kind strengthen the case for multi-messenger campaigns along the lines discussed above.

Pulsar timing trrays are likely to detect a background of gravitational waves from the inflationary era, cosmic strings or binary supermassive black holes. The stringent constraints on such backgrounds are already enabling models of black-hole evolution in merging galaxies and also models of cosmic strings to be ruled out.

A.6 LISTENING TO THE MOST ENERGETIC EVENTS IN THE UNIVERSE

Modern astronomy has revealed a diverse and exotic Universe, full of explosive, ultra-energetic phenomena which remain enigmatic decades after their initial discovery. Examples include:

- *Supernovae*: These cosmic explosions arise from the sudden gravitational collapse of a star, followed by a dramatic explosion, during which many of the chemical elements that make up our human bodies and our planet are synthesized; the mechanism of the explosion is not understood.
- *Gamma-ray bursts:* These intense bursts of radiation last only a few seconds, yet emit more energy than a star in its entire life time; the mechanism is not understood.
- *Magnetar bursts:* These ultra-magnetized neutron stars sporadically emit intense bursts of radiation, so powerful that they can disrupt radio communications and power transmission on Earth.

All these events involve strong gravitational fields and are potential sources of gravitational waves. (1) The visible display of a supernova represents the outer layers of the star being ejected by the central core collapse. However, these electromagnetic observations carry little information about the actual core collapse and the mechanism that turns this collapse into an outgoing explosion. Gravitational waves from the core collapse will carry direct clues to the motions within the core that drive the supernova. Long gamma-ray bursts have also been connected with core collapse supernovas, and may represent the most energetic of a range of supernova progenitors. (2) Short gamma-ray bursts may arise from coalescing neutron stars, which are electromagnetically invisible until they merge. Simultaneous gravitational-wave and gamma-ray observations would definitively identify their progenitors and masses; gravitational wave polarization data would reveal the orbital inclination angle and hence the beaming of the gamma-rays, with important implications for the source physics and electromagnetic census of the source population. (3) The gravitational waves from magnetars are intrinsically much weaker than those from binary black holes or neutron stars, but the comparative closeness of these galactic sources makes their gravitational wave emissions potentially observable, depending on whether the burst energy source is internal or magnetospheric in origin. Thus, the gravitational window on these phenomena will help astronomers resolve puzzles that have persisted for decades.

References

[1] Everitt et al. 2011, PRL, 106, 221101
[2] Will 2006, Living Rev. Relativity, 9, 3
[3] Hughes 2010, arXiv:1002.2591
[4] Pretorius 2006, CQGra, 23, S529
[5] van Hasteren & Levin 2010, MNRAS, 401, 2372
[6] Cutler et al. 2014, PRD, 89, 042003
[7] Abadie et al. 2010, CQGra, 27, 173001
[8] Bildsten 1998, ApJL, 501, L89
[9] Sammut et al. 2014, PRD, 89, 043001
[10] Riles 2013, PrPNP, 68, 1
[11] Bennett et al. 2010, MNRAS, 409, 1705
[12] Alford et al. 2008, RvMP, 80, 1455
[13] Nissanke et al. 2013, arXiv:1307.2638
[14] Roedig et al. 2014, ApJ, 785, 155
[15] Kocsis et al. 2011, PRD, 84, 024032
[16] Milosavljevic & Phinney 2005, ApJL, 622, L93

B ACRONYMS USED IN THIS DOCUMENT

2MTF – 2MASS Tully-Fisher (survey) http://ict.icrar.org/2MTF
6dFGS – The 6dF Galaxy Survey http://oldweb.aao.gov.au/local/www/6df

AAL – Astronomy Australia Limited http://astronomyaustralia.org.au
AAO – Australian Astronomical Observatory http://www.aao.gov.au
AAT – Anglo-Australian Telescope http://www.aao.gov.au/about-us/AAT
ACIGA – Australian Consortium for Interferometric Gravitational Astronomy http://www.anu.edu.au/physics/ACIGA
AGB – asymptotic giant-branch (star)
AGN – active galactic nucleus
ALMA – Atacama Large Millimeter/submillimeter Array http://www.almaobservatory.org
AMRFP – Access to Major Research Facilities Program (grant scheme supported by ANSTO through 2012) http://www.ansto.gov.au/ResearchHub/UserAccess/MajorResearchFacilitiesProgram
AMS Accelerator Mass Spectroscopy (facility, at ANU) http://physics.anu.edu.au/nuclear/research/ams
ANITA – Australian National Institute for Theoretical Astrophysics http://anita.edu.au
ANSTO – Australian Nuclear Science and Technology Organisation http://www.ansto.gov.au
ANU – Australian National University http://www.anu.edu.au
ARA – Askaryan Radio Array http://ara.physics.wisc.edu
ARC – Australian Research Council http://www.arc.gov.au
ASKAP – Australian Square Kilometre Array Pathfinder http://www.atnf.csiro.au/projects/askap
ATCA – Australia Telescope Compact Array http://www.narrabri.atnf.csiro.au
ATNF – Australia Telescope National Facility http://www.atnf.csiro.au

BBN – big bang nucleosynthesis
BETA – Boolardy Engineering Test Array
BNS – binary neutron star

CAASTRO – ARC Centre of Excellence for All-sky Astrophysics http://www.caastro.org
CADOR – Coordination and Data Analysis for Robotic Observatories http://cador.obs-hp.fr
CALET – CALorimeteric Electron Telescope http://calet.phys.lsu.edu
CASS – CSIRO Astronomy and Space Science
CCD – charge-coupled device
CERN – European Council for Nuclear Research http://home.web.cern.ch
CHIME – Canadian Hydrogen Intensity Mapping Experiment http://chime.phas.ubc.ca
CNO – carbon, nitrogen, and oxygen (nuclei)
CoGeNT – Coherent Germanium Neutrino Technology experiment http://cogent.pnnl.gov
CRAFT – Commensal Real-time ASKAP Fast Transients (survey)
CRESST – Cryogenic Rare Event Search with Superconducting Thermometers http://www.cresst.de CRIS – Collaborative Research Infrastructure Scheme
CSIRO – Commonwealth Scientific and Industrial Research Organisation http://www.csiro.au
CSP – Central Signal Processor http://www.skatelescope.org/skadesign/wp/csp
CSU – Charles Sturt University, NSW http://www.csu.edu.au
CTA – Cherenkov Telescope Array http://www.mpi-hd.mpg.de/hfm/CTA/CTA_home.html
CVN – Chinese VLBI Network http://www.astro.sci.yamaguchi-u.ac.jp/eavn/aboutcvn.html

DAMA – DArk MAtter (observatory) http://people.roma2.infn.it/~dama
DAMPE – DArk Matter Particle Explorer http://dpnc.unige.ch/dampe
DRAGONS – Dark-ages Reionization and Galaxy Formation Simulation

EFT – equivalent full-time (personnel)
EIF – Education Investment Fund https://www.education.gov.au/education-investment-fund
ELT – Extremely Large Telescope
E-ELT – European ELT http://www.eso.org/sci/facilities/eelt
eROSITA – extended Roentgen Survey with an Imaging Telescope Array http://www.mpe.mpg.de/eROSITA
ESA – European Space Agency http://www.esa.int
ESO – European Southern Observatory http://www.eso.org
ET – Einstein Telescope http://www.et-gw.eu

FAIR – Facility for Antiproton and Ion Research (GSI) http://www.fair-center.eu
FAST – Five hundred metre Aperture Spherical Telescope http://fast.bao.ac.cn
Fermi-LAT – *Fermi* Large Area Telescope http://www-fermi.stanford.edu
FIGARO – France-Italy GAmma Ray burst afterglow Observation
FRB – fast radio burst
FRIB – Facility for Rare Isotope Beams (MSU) http://www.frib.msu.edu

GALAH – GALactic Archaeology with HERMES (survey) http://www.mso.anu.edu.au/galah/home.html
GBT – Green Bank Telescope http://science.nrao.edu/facilities/gbt
GEO600 – British-German interferometric gravitational-wave detector http://www.geo600.org
GMRT – Giant Metrewave Radio Telescope, Pune, India http://gmrt.ncra.tifr.res.in
GMT – Giant Magellan Telescope http://www.gmto.org
GPS – (HESS) Galactic Plane Survey
GPU – graphics processing unit
GRACE – Gravity Recovery and Climate Experiment http://www.csr.utexas.edu/grace/
GRB – gamma-ray burst
GROND – Gamma-Ray Burst Optical/Near-Infrared Detector, La Silla, Chile http://www.mpe.mpg.de/~jcg/GROND
GSI – Gesellschaft für Schwerionenforschung http://www.gsi.de
GW – gravitational wave
GWIC – Gravitational Wave International Committee http://gwic.ligo.org
GZK – Greisen–Zatsepin–Kuzmin (effect)

HAWC – High-Altitude Water Cherenkov Observatory http://www.hawc-observatory.org
HEASARC – High Energy Astrophysics Science Archive Research Center http://heasarc.gsfc.nasa.gov
HERMES – High Efficiency and Resolution Multi Element Spectrograph http://www.aao.gov.au/science/instruments/current/HERMES
HESS/HESS-II – High Energy Stereoscopic System http://www.mpi-hd.mpg.de/hfm/HESS
HIAF – Heavy Ion Accelerator Facility http://physics.anu.edu.au/nuclear/hiaf.php
HLX – hyper-luminous X-ray source
HST – Hubble Space Telescope http://spacetelescope.org
HTRU – High Time Resolution Universe (survey) http://astronomy.swin.edu.au/pulsar/?topic=hlsurvey
HATNet – Hungarian-made Automated Telescope Network http://hatnet.org

IAC – imaging air Cerenkov (technique)
IAU – International Astronomical Union http://www.iau.org
ICT – CSIRO Computational Informatics (division) http://www.csiro.au/ICT
IFU – integral field unit (spectroscopy)
IPTA – International Pulsar Timing Array http://www.ipta4gw.org
ISM – inter-stellar medium

JEM-EUSO – Japanese Experiment Module Extreme Universe Space Observatory http://jemeuso.riken.jp
JINA – Joint Institute for Nuclear Astrophysics, NSCL, MSU http://www.jinaweb.org
JPL – Jet Propulsion Laboratory, CalTech http://www.jpl.nasa.gov
JWST – James Webb Space Telescope http://www.jwst.nasa.gov

KAGRA – Kamioka Gravitational Wave Detector http://gwcenter.icrr.u-tokyo.ac.jp
KAT – Karoo Array Telescope, South Africa (precursor to MeerKAT)
KVN – Korean VLBI Network http://kvn-web.kasi.re.kr

LBA – Long Baseline Array http://www.atnf.csiro.au/vlbi
LCGT – Large-scale Cryogenic Gravitational wave Telescope http://gw.icrr.u-tokyo.ac.jp/lcgt/
LIEF – Linkage, Infrastructure, Equipment and Facilities (grant program) http://www.arc.gov.au/ncgp/lief/lief_default.htm
LIGO – Laser Interferometer Gravitational-Wave Observatory http://www.ligo.org
LISA – Laser Interferometer Space Antenna http://lisa.nasa.gov
LOFAR – Low-frequency Array http://www.lofar.org
LOFT – Large Observatory For X-ray Timing http://www.isdc.unige.ch/loft
LOOC-UP – Locating and Observing Optical Counterparts to Unmodeled Pulses http://cgp.anu.edu.au/research-streams/research-datatheory/looc-up
LUNASKA – Lunar Ultra-high-energy Neutrino Astrophysics using SKA http://www.physics.adelaide.edu.au/astrophysics/lunaska
LUX – Large Underground Xenon (dark matter experiment) http://lux.brown.edu
LVC – LIGO-Virgo Scientific Collaboration

MAGIC – Major Atmospheric Gamma Imaging Cherenkov (telescope) http://magic.mpp.mpg.de
MAXI – Monitor of All-sky X-ray Image http://maxi.riken.jp

MeerKAT – extension of the South African KAT telescope ("more of KAT") http://www.ska.ac.za/meerkat
MERLIN – Multi-Element Radio Linked Interferometer Network http://www.merlin.ac.uk
MILAGRO – water Cherenkov EAS detector located near Los Alamos, NM http://umdgrb.umd.edu/cosmic/milagro.html
MIT – Massachusetts Institute of Technology, Boston, USA
MOST – Molonglo Observatory Synthesis Telescope http://www.physics.usyd.edu.au/sifa/Main/MOST
MRO – Murchison Radio astronomy Observatory, WA, Australia
MWA – Mileura Widefield Array http://www.mwatelescope.org

NASA – National Aeronautics and Space Administration http://www.nasa.gov
NCI – National Computational Infrastructure http://nci.org.au
NCRIS – National Collaborative Research Infrastructure Strategy https://www.education.gov.au/national-collaborative-research-infrastructure-strategy-ncris
NICER – Neutron Star Interior Composition Explorer http://heasarc.gsfc.nasa.gov/docs/nicer
NRAO – National Radio Astronomy Observatory, US http://heasarc.gsfc.nasa.gov/docs/nicer/
NSF – National Science Foundation (US) http://www.nsf.gov
NTT – New Technology Telescope, La Silla, Chile (ESO) http://www.eso.org/sci/facilities/lasilla/telescopes/ntt.html
NuSTAR – Nuclear Spectroscopic Telescope Array http://www.nustar.caltech.edu

OPAL – On-line Proposal Applications & Links http://opal.atnf.csiro.au

PAF – phased-array feed
PPTA – Parkes Pulsar Timing Array http://www.atnf.csiro.au/research/pulsar/ppta
PTA – Pulsar Timing Array
PWN – pulsar wind nebula(e)

QCD – quantum chromo-dynamics

RIKEN – Japan's largest and most comprehensive research organization http://www.riken.jp
ROSAT – ROentgen SATellite (X-ray mission) http://www.mpe.mpg.de/xray/wave/rosat
ROTSE – Robotic Optical Transient Search Experiment http://www.rotse.net

SAMI – Sydney Australian Astronomical Observatory Multi-object Integral Field Spectrograph survey http://sami-survey.org
SKA – Square Kilometre Array https://www.skatelescope.org
SKAMP – SKA Molongolo Prototype http://www.physics.usyd.edu.au/sifa/Main/SKAMP
SMARTS – Small & Moderate Aperture Research Telescope System http://www.astro.yale.edu/smarts
SN – supernova
SNR – supernova remnant
SSimPL – Survey Simulation PipeLine

TAO – Theoretical Astrophysics Observatory https://tao.asvo.org.au
TAROT – Télescopes à Action Rapide pour les Objets Transitoires http://tarot.obs-hp.fr/tarot
TeVCat – Online catalog for TeV astronomy http://tevcat.uchicago.edu

UHE – ultra-high energy
UWA – University of Western Australia http://www.uwa.edu.au
UWB – ultra wide-band

VAST – Variables and Slow Transients http://www.physics.usyd.edu.au/sifa/vast
VERA – VLBI Exploration of Radio Astrometry http://www.miz.nao.ac.jp/en/content/project/vera-project
VERITAS – Very Energetic Radiation Imaging Telescope Array System http://veritas.sao.arizona.edu
V-FASTR – VLA Fast Radio transients experiment https://safe.nrao.edu/vlba/vfastr
VHE – very high-energy
VLA – Very Large Array, Socorro, NM http://www.vla.nrao.edu
VLBA – Very Long Baseline Array https://science.nrao.edu/facilities/vlba
VLBI – very-long baseline interferometry
VLT – Very Large Telescope http://www.eso.org/public/teles-instr/vlt
VO – Virtual Observatory
VOEvent – IVOA standard for transmitting information about transient events; see http://wiki.ivoa.net/twiki/bin/view/IVOA/IvoaVOEvent
VPAC – Victorian Partnership for Advanced Computing https://www.vpac.org

WALLABY – ASKAP HI All-Sky Survey http://www.atnf.csiro.au/research/WALLABY
WHT – William Herschel Telescope, La Palma, Canary Is. http://www.ing.iac.es/Astronomy/telescopes/wht
WIMP – weakly-interacting massive particle
WNSHS – Westerbork Northern Sky HI survey http://www.astron.nl/~jozsa/wnshs
WSRT – Westerbork Synthesis Radio Telescope http://www.astron.nl/radio-observatory/astronomers/wsrt-astronomers

XMM-Newton – X-ray Multi-Mirror mission http://xmm.esac.esa.int
XRB – X-ray binary