Australia's National
Science Agency

Parkes Future Science Case: 2020 onwards

Jimi Green,

Phil Edwards, George Hobbs, Mark Bowen, Simon Johnston, Chris Phillips, Stacy Mader, Andrew Cameron, Charlotte Sobey, George Heald, Cormac Reynolds, Chenoa Tremblay, Vanessa Moss, Baerbel Koribalski, Jane Kaczmarek, Robert Hollow, Dick Manchester, John Reynolds, Elaine Sadler, Tasso Tzioumis, *and other authors to follow*

June 2020

Contents

1 Executive Summary 2

2 Background 3

3 The Parkes 64m Radio Telescope 4

3.1 The MEDUSA backend 5

3.2 Parkes & the Long Baseline Array (LBA) 6

4 Science with Parkes 7

4.1 Scientific impact to date 7

4.2 Current projects 8

4.3 Contracted time 8

5 International Landscape 9

6 Future Science with Parkes 10

6.1 Transients and Fast Radio Bursts 10

6.2 Pulsars 10

6.3 Atomic hydrogen across cosmic time 11

6.4 Molecular lines 12

6.5 Other science 13

7 Other Applications for Parkes 13

7.1 RFI Mitigation 13

7.2 Search for Extra Terrestrial Intelligence (SETI) 14

7.3 Space 15

7.4 Research training and education 15

7.5 The 12-m Parkes Test Facility 16

8 Conclusion and Recommendations 16

1 Executive Summary

The iconic CSIRO Parkes 64 m radio telescope has been in operation since 1961 and has continually been at the forefront of science by virtue of its world class astronomical research enabled by its ever-evolving cutting-edge technology (including regular upgrades to its front-end receivers, back-end instrumentation, computer processing capabilities, and extensions of the solid-panel surface). "The Dish" played a key role in the discovery of quasars; has discovered more than half of the known pulsars, including the first double pulsar; pioneered the field of Fast Radio Bursts; and has mapped the southern skies in continuum, neutral hydrogen, and several spectral lines. It will continue to be the only large single-dish facility in the southern hemisphere dedicated to radio-astronomy through this decade. It will uniquely provide research output with innovative world-leading technology, and provide the crucial single-dish data for the new and upgraded interferometers in the southern hemisphere. This document describes at a high level the scientific and operational direction of the Parkes telescope in the era after 2020, when we approach the construction and operation of the Square Kilometre Array (SKA)[1].

The key science areas from 2020 onwards are identified as:

- Accurate measurements of Fast Radio Burst (FRB) fluences [Section 6.1]
- Unique wide-bandwidth studies, follow-up and discoveries of pulsars [Section 6.2]
- Intensity mapping of the neutral universe and studies of atomic hydrogen across cosmic time [Section 6.3]
- Unique simultaneous multi-transition molecular line studies of the southern sky [Section 6.4]
- Very Long Baseline Interferometric (VLBI) science enabled by Parkes being an integral and flexible component of the Long Baseline Array (LBA) [Sections 3.2 and 6.5]
- Science enabled by world-leading SKA-oriented technology development (ultra-wide bandwidths and wide-fields enabled by phased array feeds) [Sections 3 and 6]
- Providing essential single-dish ('zero-baseline') data for atomic hydrogen, continuum and polarisation projects with the Australian Square Kilometre Array Pathfinder (ASKAP) [Sections 6.3 and 6.5]
- Spacecraft tracking and bi-static radar (through collaboration with the Canberra Deep Space Communication Centre, CDSCC) [Section 7.3]

The Parkes telescope has a pivotal role for the Australian and international communities in providing inclusive hands-on access, for researchers and students alike, to world leading science with state-of-the-art technology. It will continue to educate and inspire the future users of the SKA.

[1] This document assumes the SKA will be under construction during the period 2021 to 2030 and enter early science at the end of this decade. It also assumes that the mid-frequency SKA pathfinders, ASKAP and MeerKAT, will conduct their survey science observations during the period 2020-2030.

2 Background

This document has been compiled from previous community discussions (through the Australia Telescope User Committee meetings), and the science cases for funding proposals, and will be iterated with the incorporation of community input through a workshop in 2020. It follows an earlier ATNF document, ATNF Science Priorities 2010 – 2015, and is a counterpart to the 'ATCA Future Science Case: 2020 onwards' document. Some of the most significant changes in the scientific and technical landscape since 2015 include:

2015: an Australian Research Council (ARC) Linkage Infrastructure Equipment and Facilities ('LIEF') grant was awarded for $0.7M to develop and commission an Ultra-Wide bandwidth Low frequency receiver ('UWL').

2015: The LIGO detection of gravitational waves from a merging blackhole binary (and subsequent detections thereafter). A key long-term project on Parkes is the Parkes Pulsar Timing Array, which seeks ultra-low-frequency gravitational waves from coalescing supermassive binary black holes (highly complementary to LIGO/VIRGO discoveries).

2017-2018: The successful commissioning of the UWL receiver (Hobbs et al. 2020). Now provided as a National Facility instrument, along with ongoing developments of additional modes of operation.

2019: ASKAP entering science operations in its full 36-dish mode, with a 30 deg^2 field of view at frequencies between 700 MHz and 1.8 GHz. This opens up exciting new scientific synergies between ASKAP and Parkes, whilst increasing demands on the overall ATNF operations budget.

2019: ASKAP localisation (with ATCA assistance) of Fast Radio Bursts (FRBs) to their host galaxies, further establishing Australia in a leading position following Parkes' ground-breaking work in the field.

2019: The award of 2020 ARC LIEF funding for $1.15M for a new cryogenically cooled Phased Array Feed ('Cryo-PAF').

The period from 2015 to 2020 has also seen the commissioning of MeerKAT, the Five-hundred-metre Aperture Spherical Telescope (FAST), and other facilities such as CHIME, such that the international landscape in which Parkes operates has changed significantly over the past five years.

Parkes has a current direct operating cost of around $2.4M per annum (excluding overheads) and has diversified its operating model by attracting external revenue in return for dedicated telescope time. In the last 5 years this has included the Breakthrough Prize Foundation, National Astronomical Observatories Of China (NAOC), Chinese Academy of Sciences (CAS) and the National Aeronautics and Space Administration (NASA), comprising of order 40% of the available telescope time for any given semester.

Given the changing landscape, it is timely to examine the scientific case for Parkes over the next decade before the SKA becomes available.

3 The Parkes 64m Radio Telescope

Figure 1: The CSIRO Parkes Radio Telescope

The 64-m Parkes Radio Telescope (Figure 1) is located 380 km west of Sydney, with a suite of receivers covering 700 MHz to 26 GHz (Table 1). The intention is that the Parkes receiver fleet will evolve over the period 2020-2030 to streamline to a single focus cabin installation providing for all of the current science observing needs, whilst also providing new capabilities. The technical evolutions will include:

- The Cryogenically Cooled Phased Array Feed (Cryo-PAF)**,** covering ~700 – 1800 MHz with ~3 times the 20cm Multibeam field of view (the Cryo-PAF will replace and exceed the Multibeam receiver's functionality). The Cryo-PAF was successfully awarded ARC LIEF funding commencing 2020. This will be one of the first such systems in the world, providing a unique capability for Parkes.
- A planned Ultra-Wide-bandwidth High frequency receiver (UWH), covering the existing frequency range of 4 GHz to at least ~25 GHz, possibly up to 32 GHz, likely in two bands.
- Potentially high-frequency phased array feed(s), as there is longer-term interest in developing such a technically challenging system, including at 20 – 25 GHz frequencies.
- A shift of VLBI capability from the traditional Data Acquisition System (DAS) to the Graphics Processor Unit (GPU)-based signal processor system (known as MEDUSA).

The UWL effectively replaces the existing 10/50 receiver, the H-OH receiver, and the S-band component of the Australia Telescope Multiband receiver. The UWH would effectively replace the 'Old Meth', Mars, K/Ku, 13mm and C and X components of the AT Multiband, as well as filling in the gaps in frequency coverage, to provide a new capability covering this wide frequency range contiguously. All these legacy narrow-band receivers can be decommissioned once the respective wideband receiver has been fully commissioned for National Facility use. The additional spacecraft tracking receivers (with native circular polarisation feeds), Galileo (2.0 – 2.5 GHz) and Mars (8.0 –

9.0 GHz), can only be decommissioned once the wideband receivers can digitally replicate the polarisation to a standard satisfactory to space agencies.

	FREQUENCY RANGE (GHZ)	BANDWIDTH (MHZ)	MID-BAND TSYS (K)	NATIVE POLARISATION	PROPOSED TIMELINE
10/50	0.700-0.764/2.600-3.600	64/1000	35/40	linear	Replaced by UWL
Multibeam	1.23-1.53	384	28	linear	Replaced by CryoPAF
Cryo-PAF	0.700-1.800*	384-1100*	20*	linear	Design & construction
UWL	0.70-4.20	3500	21	linear	Installed & in use
H-OH	1.20-1.80	500	25	linear	Replaced by UWL
Galileo	2.15-2.27/2.20-2.50/2.29-2.30	120/300/10	18	circular	Replaced by UWL
'Old Meth'	5.90-6.80	300	55	circular	Replaced by UWH
Mars	8.10-8.50	1000	25	circular	Replaced by UWH
K/Ku Band	21.00-24.00/12.00-15.00	500	105/80	linear	Replaced by UWH
13-mm	16.00-26.00/21.00-22.30	1000/1000	90	linear/circular	Replaced by UWH
AT Multiband	2.20-2.50/4.50-5.10/8.10-8.70	300/500/500	80/50/120	linear/1 pol circular	Replaced by UWL/H
UWH	4.00-15.00/15.00-27.00^	3500-12000*	21*	linear	Design & construction

Table 1: Characteristics of the Parkes receiver fleet. * indicates target values, still under design / construction. ^ indicates could be 4.00-18.00/18.00-32.00 potentially, dependent on community discussion in preparation for funding proposal.

3.1 The MEDUSA backend

The UWL is served by a Graphics Processor Unit (GPU) based backend called 'MEDUSA'. This was initially installed to serve the Max Planck Institute ASKAP PAF and then transitioned to the primary backend for the UWL and forthcoming receivers. As an off-the-shelf GPU provision, it is possible to regularly upgrade the units for additional processing power, and through this process it is intended to also serve the Cryo-PAF and UWH receivers. Currently it can generate 1 to 4 polarisation products across the whole band (captured in 26 128-MHz sub-bands) in pulsar search, pulsar fold or spectral line modes. Pulsar fold data can be channelised from 64 to 4096 channels, with 8 to 4096 rotational phase bins, and sub-integrations between 8 and 60 seconds. Pulsar search data can be channelised between 8 and 4096 channels, with a sampling interval of 1 microsecond to 1 second, with 1 to 8 bits. Spectral line data can be channelised to 2,097,152 channels per sub-band (equivalent to a frequency resolution of 61 Hz), with a sampling interval between 0.262144 and 60 seconds[2].

[2] Further details can be found in the online Parkes Users Guide: https://www.parkes.atnf.csiro.au/observing/documentation/users_guide/html/pkug.html

3.2 Parkes & the Long Baseline Array (LBA)

Parkes can be linked with other telescopes, including the Australia Telescope Compact Array, the Hobart and Ceduna antennas operated by the University of Tasmania, telescopes in New Zealand operated by Auckland University of Technology and the South African Hartebeesthoek telescopes, to form the southern hemisphere Long Baseline Array (LBA).

The long baselines of the LBA, up to ~10,000 km, allow it to image compact radio sources with angular resolutions ~15,000 times higher than is possible with Parkes alone. Parkes and the ATCA are the most sensitive regularly available elements of the LBA, and their presence within the array improves the effectiveness of the 12 m class telescopes at Yarragadee, Katherine and Warkworth. The full 64m collecting area is used at low frequencies, but at higher frequencies only the inner 55m (of perforated aluminium panels) is used.

Parkes' participation in the LBA is currently limited by the availability of higher frequency receivers (see Table 1), typically only installed for dedicated VLBI weeks that occur 1 to 2 times per semester (equating to ~4 weeks per annum). However, the advent of the UWH will allow Parkes to have greater and more flexible participation, enabling an increase in the time dedicated to the LBA to be considered (in recent years the LBA has been the most oversubscribed facility, with factors in excess of 2.)

The LBA, including Parkes, has a key role in the era of the SKA to provide high-resolution follow-up of new discoveries at SKA1-MID frequencies, as well as being a component of SKA1-VLBI. There are plans to develop an African VLBI Network, refurbishing ex-communications antennas, however it is not clear how extensive this array will become over the next decade. In any case, the longest VLBI baselines for observations of southern sources will come by combining the phased-up SKA1-MID with elements of the existing LBA (also providing key east-west baselines, compared to the predominantly north-south baselines provided by connections to the African and European networks, see the ATCA Future Science Case for demonstrations of these).

The Cryo-PAF, in conjunction with the multi-beam capability of the BIGCAT tied array system at ATCA and the planned CRACO tied array at ASKAP, affords a unique opportunity to exploit multi-directional VLBI observations. The application of this is two-fold: first, it will enable a rapid surveying capability with multiple sources being observed simultaneously, for example in the follow-up of many thousands of detections from the ASKAP EMU survey to determine source compactness; second, it will permit a truly simultaneous multi-view calibration approach to provide ultra-precise (~micro arcsecond) astrometry (Rioja et al. 2017). This will be an important pathfinder for SKA1-VLBI, whose science case depends heavily on the kind of ultra-precise astrometry that cannot be routinely achieved with the current generation of relatively small field-of-view VLBI instruments.

A further VLBI enhancement will be the ability to do single-baseline PAF to PAF VLBI in the 700 to 1400 MHz band – a unique capability worldwide, and one which uniquely enables aspects of redshifted HI absorption studies (see Section 6.3).

4 Science with Parkes

4.1 Scientific impact to date

The simplest measures of scientific impact are the number of publications resulting from use of the telescope and how much these are cited in the scientific literature. The rate of publications using Parkes observations has typically been in the region of 40-50 papers per annum, dropping to 30-40 in 2017-2018 with the impact of commissioning the Max Planck Institute PAF in 2016 and the UWL in 2017. The rate has returned to 44 publications in 2019, which has further significance given a reduced time allocation for proposal driven research, with the contracted time allocation (taking of order ~30-40% of telescope time in recent semesters). These publications are in a range of high impact publications, including Science and Nature, and are significantly cited.

Parkes has made high-impact contributions to a wide variety of research areas, including: all-sky continuum surveys such as the 408 MHz continuum maps of Haslam et al. (1982) and Parkes-MIT-NRAO 4.8 GHz survey (Griffith and Wright 1993); supernova remnants (Clark and Caswell 1976); the Large and Small Magellanic Clouds and Magellanic stream (Stanimirovic et al., 1999, Kim et al. 2003, Putman et al. 2003); HII regions (Caswell and Haynes 1987) and a polarisation all sky survey, SPASS (Caretti et al. 2019).

The installation of the 20cm multibeam receiver in 1997 enabled two large projects to be undertaken, HIPASS – the HI Parkes All Sky Survey (Barnes et al. 2001, Meyer et al. 2004, Koribalski et al. 2004) and the Parkes Multi-beam Pulsar Survey (Manchester et al. 2001). Over the last two decades, pulsar and transient astronomy (both searching for new pulsars and high precision timing of known pulsars) has been a significant focus of the Observatory's work, taking ~2/3 of the scheduled observing time. This has led to high profile papers on the double pulsar (Lyne et al. 2004), magnetars (e.g., Camilo et al. 2007), RRATs – Rotating Radio Transients (McLaughlin et al. 2007), and the discovery of Fast Radio Bursts (Lorimer et al. 2007). The multibeam further enabled studies of Fast Radio Bursts with the SUPERB project (Keane et al. 2018). Bespoke receivers have also been used for dedicated survey work, such as with the GMIMS project (Wolleben et al. 2019). This brief list of examples illustrates the range of science Parkes has contributed to, with further examples given elsewhere in this document.

4.2 Current projects

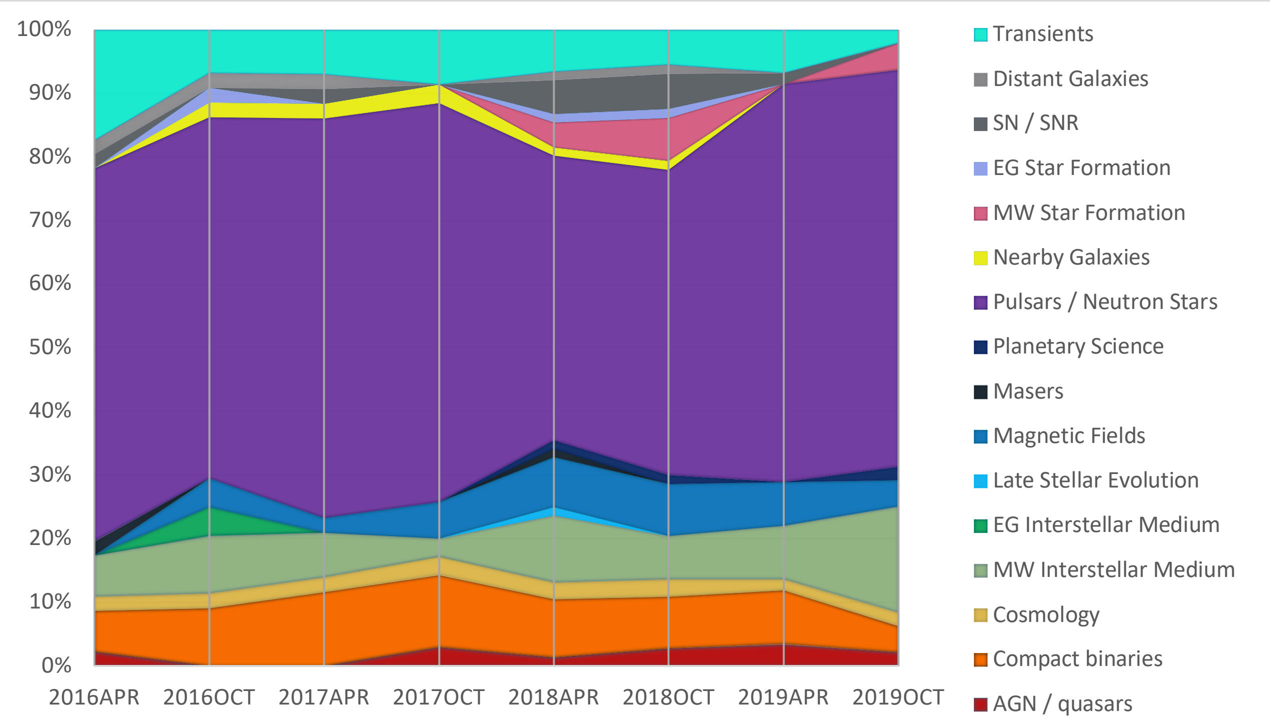

Figure 2: Science areas of successful Parkes proposals since 2016 (excluding time allocated to purchased time). Data compiled by Jamie Stevens.

Current science with Parkes is dominated by that enabled by the UWL receiver. This includes wide-bandwidth studies of pulsars, follow-up of transients, and renewed interest in spectral line studies. A plot of the science, based on proposal key words, conducted over recent years (by semester) is provided in Figure 2.

4.3 Contracted time

Parkes has had three external contracts for dedicated telescope time in the last 5 years:

- With the Breakthrough Prize foundation for the Breakthrough Listen project to Search for Extra-Terrestrial Intelligence (SETI) and conduct commensal transient and pulsar studies (with 3 publications to date), running for 5 years from November 2016. This project includes the installation of a dedicated backend at Parkes consisting of a cluster of 26 GPU-based servers capturing 8-bit voltage-level data products across the full bandwidth of the UWL;
- With the National Astronomical Observatories Of China (NAOC), Chinese Academy of Sciences (CAS) for follow-up of Five-hundred-metre Aperture Spherical Telescope (FAST) pulsar detections, running for 3 years from 2017 to 2020 (with 7 publications published or submitted to date);
- With NASA for a short-notice ~4 month contract to track the Voyager 2 probe as it left the solar system (resulting in 5 publications in *Nature Astronomy*).

5 International Landscape

Parkes remains the only large (>50m diameter) single dish telescope dedicated for radio astronomy in the southern hemisphere. Table 2 (below) provides a list of the main large telescopes currently in operation (Note that the spherical fixed dishes, Arecibo and FAST have limited sky coverage).

In the southern hemisphere, MeerKAT is now also carrying out major pulsar surveys and timing projects that were traditionally the mainstay of Parkes observing. Within the same observing band, MeerKAT has a sensitivity approximately 5 times that of Parkes. Also in the southern hemisphere, the Molonglo telescope now observes bright pulsars daily (but with a restricted observing band) and is used to search for transient events.

In the northern hemisphere, the FAST telescope (16 times the sensitivity of Parkes in the 20cm band) is now carrying out pulsar searches (but with a declination limit of approximately -15 degrees). Further new telescopes, such as those in China (including the 110m QiTai steerable dish and the 40-m Yunnan and XiAn telescopes) and in Thailand (a 40m in Chiang Mai) will also be operational within this decade. The Canadian CHIME telescope is now online and is currently the world-leader for detecting Fast Radio Bursts. ASKAP is also active in FRB research, and has the advantage over CHIME (prior to the deployment of outriggers) and Parkes of being able to localise FRBs to their host galaxy. At lower frequencies, the Murchison Widefield Array (MWA) and upgraded Giant Metre Radio Telescope (uGMRT) are operating in the low and mid frequency bands.

TELESCOPE	LATITUDE	DIAMETER	FREQUENCY RANGE
Parkes	33 S	64 m	0.70 — 26 GHz
Sardinia, Italy	39 N	64 m	0.30 — 26 GHz
TianMa, China	31 N	65 m	1.20 — 50 GHz
Lovell Telescope, Jodrell Bank, UK	53 N	76 m	0.30 — 8 GHz
Effelsberg, Germany	51 N	100 m	0.30 — 95 GHz
Green Bank Telescope, USA	38 N	100 m	0.30 — 115 GHz
Arecibo, Puerta Rico (static structure)	18 N	300 m	0.30 — 10 GHz
FAST, China (static structure)	26 N	500 m	0.07 — 3 GHz

Table 2: Large single-dish telescopes currently in operation (in order of diameter, fully steerable unless noted).

We expect that the primary users of the telescope over this the coming decade will include the traditional pulsar user community (primarily from CSIRO Astronomy and Space Science, Swinburne University of Technology, the Max Planck Institute, Sardinia Radio Telescope and University of Manchester, Jodrell Bank), and expand with growth from research communities in Asia (in particular China, Thailand and India). The interest of these communities in Parkes observations arises from the ability to have open-sky (as well as purchased) access to Parkes for commensal observations with Asian and Australian telescopes over wide-bandwidths and for confirmation/monitoring observations of objects, in particular pulsars, discovered using their telescopes. Over the past 3 years Parkes has had proposers from 25 countries, with national users comprising ~30%, those from China, the UK, the USA, and Italy each comprising ~10% and the other nationalities the remainder.

6 Future Science with Parkes

Science cases made in recent workshops in 2019 and 2020, LIEF proposals for the UWL and the Cryo-PAF, together with those at the specific Parkes October 2012 and December 2013 Australia Telescope User Committee (ATUC) meetings (available online[3]), include:

6.1 Transients and Fast Radio Bursts

Pulsar surveys using Parkes initiated (Lorimer et al. 2007) and led the field of Fast Radio Bursts (FRBs) for many years (e.g. Keane et al. 2018). The Cryo-PAF on Parkes will enable contributions relevant to this rapidly developing landscape via a survey with beam-corrected fluences at a competitive sensitivity and Dispersion Measure range. Not possible with previous systems such as the Multibeam, accurately measuring FRB fluences (with full plane sampling enabled by PAFs, e.g. Shannon et al. 2018) can break the degeneracy between the energy distribution function and its evolution. Specifically, this will allow for the observable properties of the bursts to be examined in relation to fluence, for example whether low fluence FRBs repeat more than high fluence FRBs, and whether low fluence FRBs have complex spectral structure. Parkes can characterise the fainter counterparts to ASKAP detections. The wide-field of view of the Cryo-PAF, combined with the high sensitivity and dense focal plane sampling, also allows for sensitive large-area FRB searches with detection rates exceeded only by ASKAP (after its planned coherent upgrade) and CHIME. The UWL allows for wideband follow-ups and monitoring of previously-discovered FRBs to search for repeat bursts, and can also be used to monitor other kinds of variable radio sources. Both the UWL and the Cryo-PAF allow for continued searches for transient techno-signatures as part of the Breakthrough Listen and other SETI related activities (see also Section 7.2).

6.2 Pulsars

Forthcoming headline pulsar science is likely to come from: large-scale surveys with the cryo-PAF (covering more sky than is possible with MeerKAT); ultra-wide-bandwidth observations of pulsars; high-precision pulsar timing, the flexibility for following-up new discoveries (such as potential pulsar-black-hole systems discovered in continuum imaging surveys); and the science that can arise from flexible observing systems and storing raw data files (e.g. discovering “the unknown”, using unusual observing and data recording modes).

The primary pulsar surveys will be carried out with the Cryo-PAF. The Cryo-PAF will provide ~20K system temperature across a ~1.5 degree field of view, and can survey the sky to a depth some 2.5

[3] https://www.atnf.csiro.au/management/atuc/2012oct/science_meeting/programme.html and https://www.atnf.csiro.au/management/atuc/2013dec/science_meeting/programme.html

times better (per unit time) than the previous multibeam surveys. Parkes will therefore carry out a large-area survey, predominantly at mid Galactic latitudes where the density of millisecond pulsars on the sky is highest. This could for example cover 4500 square degrees in 1375 hours of on-sky time. Competition and collaboration with MeerKAT and FAST surveys will ensure the best outcomes for pulsar astronomy.

The sensitive new telescopes that carry out pulsar surveys (including MeerKat and FAST) have changed the international landscape for pulsar studies. To determine the astrometric, binary and spin parameters for a new discovery it is necessary to monitor each pulsar discovery for at least one year. The slew speed for telescopes such as FAST implies that it is impractical for FAST to monitor its own discoveries. This has led to the FAST team/NAOC already purchasing significant time on Parkes for such observations. We note that Parkes cannot effectively monitor very weak pulsars discovered by FAST, but the small number of available telescopes and the expected large number of new discoveries (including from imaging surveys of point sources) implies that Parkes will continue to have an essential role in follow-up pulsar observations.

The Parkes wide-band, single pixel receiver systems (and the possibility of higher-cadence observing compared with more over-subscribed telescopes) implies that Parkes will continue to have an essential role in high-precision pulsar timing experiments. The legacy of decade-long timing baselines for a large set of millisecond and slow pulsars, which continues using the improved capabilities of the UWL, is important for a wide range of science goals, including investigating neutron star physics and pulsar emission, probing the ISM, and testing gravitational theories. Key projects will include monitoring dispersion measure and pulse shape variations for pulsar timing array experiments on MeerKAT and SKA-mid as well as long-term monitoring of pulsars that are jitter-dominated with the more sensitive telescopes. For young pulsar monitoring, Parkes is likely to observe ~250 brightest pulsars with a 4 week cadence to complement Molonglo's daily observations (which have a very small bandwidth and no polarization capability). The Cryo-PAF capability of multiple steerable beams will allow for simultaneous timing observations for pulsars within the same field of view.

Parkes pulsar data become publicly available via the CSIRO Data Access Portal[4] 18 months after observations are taken (or sooner if the proprietary period is waived), providing a valuable resource to the wider community. As of the end of 2019 the DAP has over 5000 collections, amounting to in excess of 2 Petabytes, which are viewed typically 5000 times a month.

6.3 Atomic hydrogen across cosmic time

Parkes has an extensive history of studying and mapping both Galactic and extragalactic hydrogen, including extensive maps and catalogues of the Milky Way and Magellanic system (e.g. Putman et al. 1998, 2002, 2003, McClure-Griffiths et al. 2009, Moss et al. 2013), all-sky HI surveys like HIPASS (Barnes et al. 2001, Meyer et al. 2004, Koribalski et al. 2004) and innovative techniques such as spectral stacking (Delhaize et al. 2013) and intensity mapping to a redshift of ~1. Parkes has contributed key data in advancing studies of the Magellanic system, which can only be studied in its entirety in the southern hemisphere. A deepened understanding of the role of atomic neutral

[4] https://data.csiro.au

hydrogen, particularly in the Milky Way, Magellanic system and Local Group, has important implications for studies of gas in galaxies and the role of the circumgalactic medium in conjunction with other multiwavelength data.

Parkes will undertake HI intensity mapping at redshifts up to z=1 with the new Cryo-PAF. Intensity mapping uses the cross-correlation of HI data cubes (the HI intensity field) with the optical intensity field from deep redshift surveys like WiggleZ (Drinkwater et al., 2010) to study the distribution of neutral gas at an important epoch in the history of the Universe where the star-formation rate was an order of magnitude greater than it is now. Since both the Cryo-PAF and the UWL overlap in frequency with ASKAP, Parkes can also be used alongside ATCA for follow-up observations of extragalactic HI absorption systems detected by ASKAP and search for high-velocity neutral gas outflows associated with AGN feedback (e.g. Allison et al. 2014, Reeves et al. 2016, Mahony et al. 2016). In addition, VLBI observations of these systems of a single Parkes-ASKAP baseline will make it possible to measure the size and kinematics of the gas in HI absorbers found in distant galaxies by the ASKAP FLASH survey.

Parkes also provides crucial single-dish (‘zero-baseline’) data (e.g. For et al. 2012) for ASKAP studies of Galactic, Magellanic and extragalactic HI, providing sensitivity to low surface brightness diffuse emission (e.g. McClure-Griffiths et al. 2018). The Cryo-PAF also offers a unique opportunity to study the diffuse Galactic halo in a more comprehensive way that has been possible with previous receivers, following on from existing work which has shown that high velocity halo clouds often exist as two-phase structures due to interactions with the hot halo medium (Ben Bekhti et al. 2006, Putman et al. 2011) and that there is an iceberg-like structure of neutral hydrogen in the halo on large scales (Moss et al. 2017). Results from Parkes tracing neutral hydrogen in the circumgalactic medium provide an important constraint for comparison against UV absorption studies tracing ionised hydrogen, particularly for understanding interactions with the Magellanic system (e.g. Richter et al. 2017, Fox et al. 2019).

6.4 Molecular lines

New multi-transition studies will be enabled with the wide band receivers. Parkes has traditionally conducted extensive surveys for molecular lines with the receivers it has had available, for example silicon-oxide masers at 43 GHz (Balister et al. 1977), methylidyne at 3 GHz (Whiteoak et al, 1978), methanol with the 7-beam Methanol Multibeam (Green et al. 2009), hydroxyl with the H-OH receiver (SPLASH; Dawson et al, 2014), and ammonia with the 13mm receiver (Wienen et al, 2015, 2018). New wideband receivers will provide opportunities for variability studies, particularly multi-transition masers, with the UWL able to capture multiple transitions of hydroxyl and methylidyne simultaneously. The UWH has potential to observe and study methanol, water and ammonia simultaneously. These molecular line surveys and monitoring observations will be further enhanced with polarimetric studies (from Zeeman splitting of the lines) to deduce the magnetic fields in-situ.

Comparable to the atomic hydrogen studies, Parkes can provide crucial single-dish data for ASKAP studies of Galactic hydrogen and hydroxyl in the diffuse interstellar medium. Furthermore, a high frequency receiver will enable the continuation of maser astrometry for Galactic structure and dynamics studies, through participation in the LBA. A further extension would be new surveys with a high-frequency PAF, which could undertake sensitive blind searches for water and ammonia for example with a system capable of covering the 20 – 25 GHz transitions.

6.5 Other science

There are a number of other significant science areas that will be addressed in the coming decade through utilising new technology on Parkes. This includes: broadband continuum and polarimetric studies (obtaining accurate rotation measures and providing data for ASKAP projects); studies of the physics of Active Galactic Nuclei; astrometry through VLBI observations with the LBA; multi-transition maser polarimetric studies, utilising the wide-bandwidth to obtain polarimetric information across multiple molecules, sampling different elements of the interstellar medium; and studies of cosmic particles by utilizing the field of view of the Cryo-PAF to capture radio emission from high energy particles interacting with the limb of the moon. A further science capability with the Cryo-PAF will be single baseline (with ASKAP) VLBI follow-up of ASKAP continuum detections, either directly or as a deep field. Additionally, the flexible signal processing systems, and relatively simple overall system, will enable novel science experiments that would not be possible with more complex telescopes such as MeerKAT, ASKAP or the SKA.

7 Other Applications for Parkes

7.1 RFI Mitigation

Radio Frequency Interference (RFI) affects the performance of radio telescopes unless appropriately mitigated. The advent of the new technology on Parkes allows for new methods in RFI mitigation and current work by the CASS Signal Processing Technologies group offers the possibility of building interference mitigation features into the upcoming Radio Frequency System-on-a-Chip (RFSoC) generation of hardware. The UWL receiver is currently being used to characterise the RFI environment (Figure 3) with a view to online flagging and blanking. The UWL also has a dedicated radio frequency input for interfering signals to be fed to the digitiser and exorcised. The CryoPAF receiver will allow for active RFI mitigation through nulling (in addition to RFSoC methods). The ability to do adaptive RFI mitigation, with the combination of a sensitive dish and new beamforming techniques, can allow for Parkes to push science in an increasingly RFI challenged environment. This can reap further efficiency rewards by maximizing the usable data.

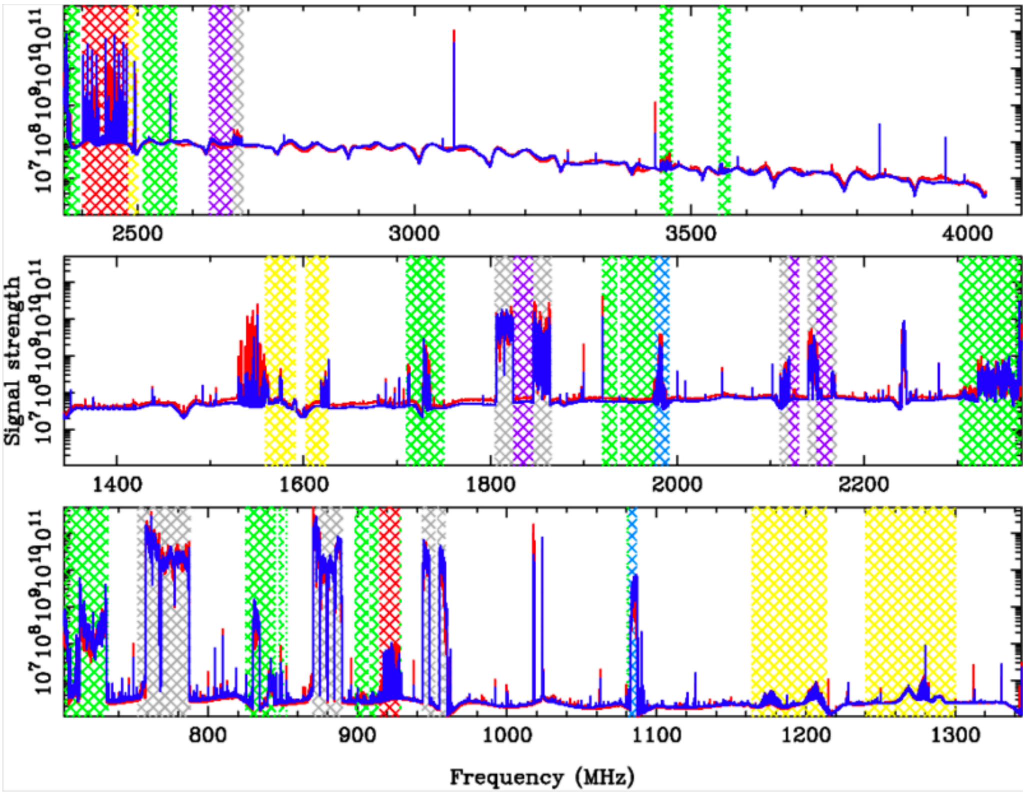

Figure 3: Radio Frequency Interference across the UWL band. Image compiled by George Hobbs. Yellow represents satellite emission; grey/purple, mobile transmission towers (operational/non-operational respectively); green, licensed receiving systems; red, wifi/bluetooth; and dark blue represents aliasing of signals.

7.2 Search for Extra Terrestrial Intelligence (SETI)

The search for intelligent life elsewhere in the Universe is one of the key science drivers of the SKA, and this combined with SKA-oriented technology development, makes Parkes a great tool for searching for techno-signatures elsewhere in the Galaxy. Since the 1970's, the frequency range between 1.4 and 1.7 GHz is considered the cleanest astrophysical window to search for signs of life (although there are also several arguments for searching for signals in the band in which we use to communicate). The Parkes UWL allows for simultaneous observations within these bands, at the high frequency resolution thought to be required for this type of search, as well as a search for new biomolecules that have transitions that sit at the lower end of the band. Parkes has a substantial history with SETI searches, with a number of projects undertaken including Blair et al. (1992) and Shostak et al. (1996), and the largest (prior to the Breakthrough Listen project) being Project Phoenix (Tarter et al. 1996), which utilised a dedicated 1.2 – 3.0 GHz receiver system. The current Breakthrough Listen project has conducted a systematic, multiple-pass large Galactic plane survey with the Multibeam receiver, a deep Galactic centre search with the UWL, as well as targeted searches of objects of interest with the UWL and legacy receivers (e.g. Price et al. 2020). These objects have included sources that might harbour techno-signatures, such as nearby stars, exoplanets, detections by NASA's Transiting Exoplanet Survey Satellite (TESS), asteroids and sources of Fast Radio Bursts. The data from this project is all publicly available (see Lebofsky et al. 2019 for details).

7.3 Space

Parkes will continue to provide an avenue for space activities as opportunity allows. This includes bi-static radar in collaboration with the Canberra Deep Space Communications Centre (CDSCC) at Tidbinbilla and spacecraft tracking (such as the 2018 NASA Voyager 2 tracking).

Bi-static radar observations of Near Earth Asteroids are performed by transmitting a radio tone from one of the Tidbinbilla antennas toward an asteroid during its close approach to Earth, and detecting the reflected radio waves with Parkes or the ATCA. Parkes participated in the initial southern hemisphere demonstrations of this technique, in the 2 GHz band, however more recent efforts have taken advantage of the ATCA's ability to receive signals at 7.1 GHz, one of the Tidbinbilla transmit frequencies, which is currently inaccessible to Parkes. Parkes, however has the advantage over the ATCA of being less sensitive to uncertainties in the orbit of the asteroid, which can be significant especially in newly discovered objects. Reception of the reflected CW (continuous wave) tone enables properties of the asteroid to be inferred, including its rotation rate, size, and surface roughness (based on polarisation ratio of received signal). A proposed upgrade to enable coded transmissions from Tidbinbilla will allow delay-Doppler 'imaging' of asteroids, as is routinely done in the northern hemisphere. A southern-hemisphere capability is important, because some Near Earth Asteroids are not visible from the northern hemisphere during their closest approach to Earth.

Both bi-static radar and spacecraft tracking require a higher frequency capability, initially provisioned by the discrete bands of the legacy receivers, but will be fully catered for with the UWH. A high frequency Phased Array Feed would also cater for space craft tracking.

7.4 Research training and education

Parkes has a considerable role in education, as an icon of Australian research endeavour. Outreach activities continue to inspire children to take up science in school and their later careers, the visitors centre is central to conveying to the public the leading astronomical research being undertaken as well as showcasing CSIRO more broadly (with visitor numbers in excess of 100,000 per annum for the last 3 years), and the long-running PULSE@Parkes programme (currently aimed at high-school students) will continue to develop and engage. Over the coming decade it is envisaged that the PULSE@Parkes programme will be enhanced and extended to serve multiple educational levels, including the possibility of undergraduate and postgraduate training courses and different science areas (beyond the current pulsar focus). This process has been instigated through CSIRO's 'On Prime' scheme (in a project called 'OPTIMUS'), whereby aspects of the astronomy community were extensively surveyed for their educational needs, developing a package outline that specifically addresses these. PULSE@Parkes is adaptable to the technology available on Parkes, having recently transitioned to the UWL receiver, and is currently preparing for the Cryo-PAF. Parkes will also have a unique capability, as one of the first facilities to have a cryogenically cooled PAF combined with a GPU backend, to train and educate researchers in PAF astronomy.

7.5 The 12-m Parkes Test Facility

The Parkes site also includes a 12-m Patriot dish, used for both engineering and scientific purposes. With a first generation ('MK I') CSIRO PAF it has conducted monitoring observations of the Vela pulsar (Sarkissian et al., 2017), and is now being outfitted with a room temperature ultra-wide bandwidth receiver. Not only will this allow the facility to conduct holography of the 64-m dish surface profile, and provide potential RFI input (at lower sensitivity), but will also allow for science itself, with regular cadence observations of bright objects, large scale molecular mapping and being part of a two element array with the 64-m.

8 Conclusion and Recommendations

Parkes has a pivotal role over the coming decade in complementing and enhancing the science of new facilities such as ASKAP, MeerKAT and FAST as we approach the SKA. The Cryo-PAF and wideband feed technology (UWL and UWH) will be central to unique frontline science with Parkes. The realisation of complete and continuous frequency coverage, combined with a flexible backend, will make Parkes an incredibly versatile instrument. The role of Parkes in the LBA will continue to be key and will be enhanced by the added flexibility that wideband receivers 'always-on' will provide. This wide-band continuous frequency coverage will also allow Parkes to dynamically react to scientific drivers, no longer requiring the lead times for separate receiver installations.

Acknowledgements

With thanks to all the staff that enable the successful development, operation, support and maintenance of Parkes. We also acknowledge with gratitude the input of the community to previous workshops and proposals that have informed this document. We also thank those who have read and provided comments on the document.

The Parkes radio telescope is part of the Australia Telescope National Facility which is funded by the Australian Government for operation as a National Facility managed by CSIRO. We acknowledge the Wiradjuri people as the traditional owners of the Observatory site.

References

Allison J. R., Sadler E. M., Meekin A. M. 2014, MNRAS, 440, 696
Balister, M., et al, 1977, MNRAS, 180, 415
Barnes, D.G., Staveley-Smith, L., de Blok, W.J.G., et al., 2001, MNRAS, 322, 486
Ben Bekhti, N., Bruns, C., Kerp, J., Westmeier, T., et al., 2006, A&A, 457, 917
Blair, D.G., Norris, R.P., Troup, E.R., et al. 1992, MNRAS, 257, 105
Carretti, E., Haverkorn, M., Staveley-Smith, L., et al., 2019, MNRAS, 489, 2330
Camilo, F., Ransom, S. M., Halpern, J. P. et al., 2007, ApJ, 666, L93
Caswell, J.L., Haynes, R.F., 1987, A&A, 171, 261
Clark, D. H. and Caswell, J. L. 1976, MNRAS, 174, 267
Dawson, J.R., et al, 2014, MNRAS, 439, 1596
Delhaize, J., Meyer, M. J., Staveley-Smith, L., Boyle, B. J., 2013, MNRAS, 433, 1398
Drinkwater, M., Jurek, R.J., Blake, C., et al., 2010, MNRAS, 1429
For, B.-Q., Koribalski, B.S., Jarrett, T.H., 2012, MNRAS, 425, 1934
Fox A. J., Richter P., Ashley T., et al. 2019, ApJ, 884, 53
Green, J.A., Caswell, J.L., Fuller, G.A., et al., 2009, MNRAS, 392, 783
Griffith, M.R and Wright A.E. 1993 AJ, 105, 1666
Haslam, C.G.T., Salter, C.J., Stoffel, H., Wilson, W.E. 1982, A&AS, 47, 1
Hobbs, G., Manchester, R.N., Dunning, A., et al., 2020, PASA, 37, 12
Keane, E.F., Barr, E.D., Jameson, A., et al., 2018, MNRAS, 473, 116
Kim, S., Staveley-Smith, L., Dopita, M.A. et al. 2003, ApJS, 148, 473
Koribalski, B.S., Staveley-Smith, L., Kilborn, V.A., et al. 2004, AJ, 128, 16
Lebofsky, M., Croft, S., Siemion, A.P.V., et al., 2019, PASP, 131, 1006
Lorimer, D. R.; Bailes, M.; McLaughlin, M. A. et al. 2007, Science, 318, 777
Lyne, A. G.; Burgay, M.; Kramer, M. et al. 2004, Science, 303, 1153
Mahony E. K., Oonk J. B. R., Morganti R., et al. 2016, MNRAS, 455, 2453
Manchester, R. N., Lyne, A. G., Camilo, F. et al., 2001, MNRAS, 328, 17
McClure-Griffiths, N.M., et al., 2009, ApJS, 18Citis1, 398
McClure-Griffiths, N.M., Denes, H., Dickey, J.M., 2018, Nature Astronomy, 2, 901
McLaughlin, M. A., Lyne, A. G., Lorimer, D. R. et al. 2006, Nature, 439, 817
Meyer, M. J., Zwaan M. A., Webster R. L., et al., 2004, MNRAS, 350, 1195
Moss, V.A., McClure-Griffiths, N.M., Murphy, T., et al., 2013, ApJS, 209, 12
Moss, V.A., Lockman, F.J., McClure-Griffiths, N.M., 2017, ApJ, 834, 155
Price, D.C., Enriquez, J.E., Brzycki, B., et al., 2020, AJ, 159, 86
Putman, M.E., Gibson, B.K., Staveley-Smith, L., et al., 1998, Nature, 394, 752
Putman, M.E., de Heij, V., Staveley-Smith, L., et al., 2002, AJ, 123, 873
Putman, Mary E.; Staveley-Smith, Lister; Freeman, Kenneth C. et al. 2003, ApJ, 586, 170
Reeves S. N., Sadler E. M., Allison J. R., et al. 2016, MNRAS, 457, 2613
Richter P., Nuza S. E., Fox A. J., et al. 2017, A&A, 607, A48
Rioja, M.J., Dodson, R., Orosz, G., Imai, H., Frey, S., 2017, AJ, 153, 105
Sarkissian, J.M., Reynolds, J.E., Hobbs, G., Harvey-Smith, L., 2017, PASA, 34, 27
Shannon, R.M., Macquart, J-P., Bannister, K.W., et al., 2018, Nature, 562, 386
Shostak. S., Ekers, R., Vaile, R., 1996, AJ, 112, 164
Stanimirovic, S., Staveley-Smith, L., Dickey, J. M. et al. 1999, MNRAS, 302, 417
Tarter, J.C., 1996, "Project Phoenix: the Australian deployment", Proc. SPIE Vol. 2704, The Search for Extraterrestrial Intelligence (SETI) in the Optical Spectrum II, Stuart A. Kingsley; Guillermo A. Lemarchand; Eds. pp 24-34
Weinen, M., Wyrowski, F., Menten, K.M., 2015, A&A, 579, 91
Weinen, M., Wyrowski, F., Menten, K., et al., A&A, 2018, 609, 125
Whiteoak, J.B., Gardiner, F.F., Sinclair, M.W., 1978, MNRAS, 184, 235
Wolleben, M., Landecker, T.L., Carretti, E., et al., 2019, AJ, 158, 44

As Australia's national science agency and innovation catalyst, CSIRO is solving the greatest challenges through innovative science and technology.

CSIRO. Unlocking a better future for everyone.

Contact us

1300 363 400
+61 3 9545 2176
csiroenquiries@csiro.au
www.csiro.au

For further information

CSIRO Astronomy and Space Science
Jimi Green
+61 8 6436 8879
james.green@csiro.au
www.atnf.csiro.au