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IAR's 60th anniversary: Prospects for low-frequency radio astronomy in South America (November 15-18, 2022)
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EXTRAGALACTIC SCIENCE WITH THE MURCHISON WIDEFIELD ARRAY

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RESUMEN

El Murchison Wide Field Array (MWA) es un telescopio radiointerferométrico de baja frecuencia situado en la zona radioastronómica más silenciosa del mundo: el Observatorio Radioastronómico de Murchison (MRO), en la zona rural de Australia Occidental. Está designado como uno de los precursores del telescopio Square Kilometre Array (SKA) Low y ha revolucionado nuestra comprensión del cielo radioeléctrico extragaláctico de baja frecuencia. El relevamiento de todo el cielo de fase I, GLEAM, y el relevamiento de seguimiento de fase II, GLEAMX, son los únicos de área amplia que cubren el cielo austral a frecuencias tan bajas. A partir de ellos ya se ha hecho posible una plétora de ciencia, desde nuevos tipos de transitorios, fuentes espectrales con picos en GHz, fuentes difusas en cúmulos y descubrimientos de emisión sincrotrón de la red cósmica. En este artículo trataré los detalles del telescopio y de estos estudios transformadores y repasaré algunos de los aspectos científicos más destacados hasta la fecha, así como las perspectivas a futuro.

ABSTRACT

The Murchison Widefield Array (MWA) is a low-frequency radio interferometric telescope based in the world's quietest radio astronomy zone: the Murchison Radio-astronomy Observatory (MRO) in rural Western Australia. It is designated as one of the Precursors to the Square Kilometre Array (SKA) Low telescope and has been revolutionising our understanding of the low-frequency extragalactic radio sky. The phase I all-sky survey, GLEAM, and the follow-up Phase II survey, GLEAMX, are the only wide area surveys to cover the Southern sky at such low frequencies. From these a wealth of science has already been enabled from new kinds of transients, GHz peaked spectrum sources, diffuse cluster sources, and discoveries of synchrotron emission from the cosmic web. In this paper I will cover the details of the telescope and these transformative surveys and go over some of the science highlights thus far as well as looking to the future.

Key Words: instrumentation: interferometers — radio continuum: general — surveys

1. INTRODUCTION

The Murchison Widefield Array (MWA) is a radio interferometric telescope based in one of the world's quietest radio astronomy zone: Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory (MRO) in rural Western Australia. Inyarrimanha ilgari bundara means 'sharing sky and stars' in the Wajarri language. In the MWA's role as a precursor to the Square Kilometre Array (SKA) Low telescope, the MWA has revolutionised our understanding of the low-frequency (70 to 300 MHz) radio sky since the commencement of operations in mid-2013.

The original "Phase I" MWA configuration of 128 tiles operated until mid-2016, during which time over 60 distinct observing programmes recorded over 20,000 hours of data and published 146 papers (for a detailed description of Phase I see Tingay et al. 2013). The operating frequency range is 70 to 300 MHz with a processed bandwidth of 30.72 MHz. The field of view of the MWA ranges from approximately 15 deg to 50 deg, depending on the frequency. The large number of baselines (8128) provides excellent u, v coverage for snapshot sampling.

After 2016, the MWA entered Phase II, which saw the introduction of expanded baselines (for full details on MWA Phase II see Beardsley et al. 2019). The Phase I configuration was expanded in mid-2016, with the addition of a further 128 tiles ushering in the "Phase II" MWA. This expansion dramatically broadened the scientific and technical capabilities of the MWA. With Phase II two distinct array configurations (each of 128 tiles) became possible: a compact configuration with a maximum baseline of around 200 m, and an extended configuration with a maximum baseline roughly 5.3 km. In its compact configuration, the Phase II MWA possesses a unique baseline distribution of the existing core tiles plus new hexagon configurations, that provides significant surface brightness sensitivity to the cosmo-

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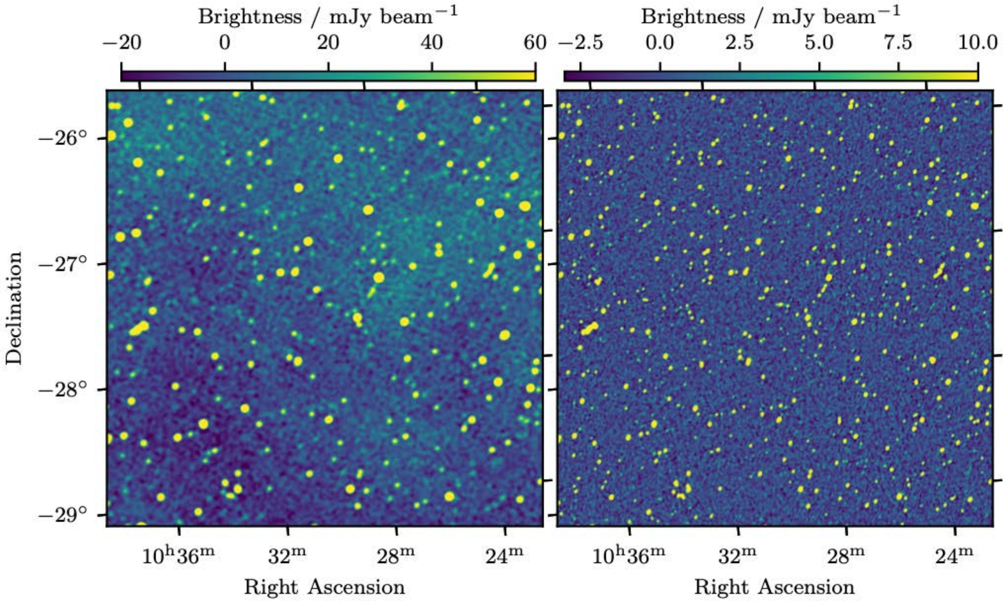

Fig. 1. Fig. 3 from Hurley-Walker et al. (2022) showing a comparison of GLEAM to GLEAM-X in the same region of sky. Here the noise in GLEAM-X is 1/6 that of the GLEAM image and there are more than double the detected sources.

logical 21 cm signal from the Epoch of Reionisation (EoR), while preserving a high-fidelity point spread function (PSF). In the extended configuration, the Phase II MWA achieves a factor two resolution improvement over Phase I, with almost an order of magnitude improvement in the confusion noise level. Additionally, it has a a far more uniform PSF leading to a significant reduction in sidelobe confusion.

In 2021 the Phase III upgrade to the MWA commenced. This Phase sees the upgrade to a new GPU-based correlator, called "MWAX" (Morrison et al. 2023). This correlator will have the power to correlate the full 256 tiles of the MWA, rather than only 128 at a time. In addition to the new correlator, Phase III will also see the commissioning of new receivers.

Four key themes drive the scientific impact of the MWA: (i) observing the 21 cm signal from the Epoch of Reionisation (EoR), (ii) Galactic and extragalactic science, (iii) the time-domain radio Universe, and (iv) Solar, heliospheric, and ionospheric phenomena. While there has already been an impressive amount of science from all the key science teams, the focus herein will be on the extragalctic and Galactic science and surveys of the MWA.

2. GALACTIC AND EXTRAGALACTIC SCIENCE

The Galactic and Extrgalactic (GEG) science team of the MWA is broken down into multiple categories:

- Galactic continuum
- Magellanic clouds and nearby galaxies
- Polarimetry
- Spectroscopy
- Radio galaxies (AGN & Star-forming)
- Clusters and the cosmic web.

There are additional several surveys that fall under the GEG science. These are the GaLactic and Extragalactic All-Sky MWA Survey (GLEAM, Wayth et al. 2015; Hurley-Walker et al. 2017, 2019; Franzen et al. 2021), the eXtended GLEAM survey (GLEAM-X Hurley-Walker et al. 2022), and the MWA Interestingly Deep Astrophysical Survey (MIDAS, in-prep) and the GAMA23 OverwheLming Deep (GOLD) Survey (in prep).

This section will give an overview of these surveys and highlight some selected works from the different sub-topics.

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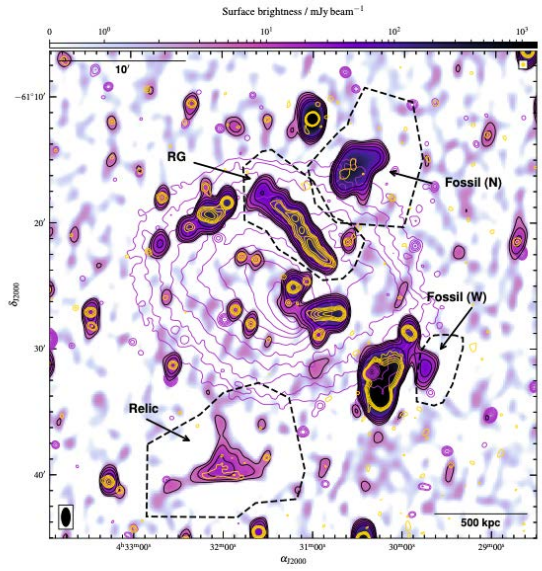

Fig. 2. Fig. 1 from Duchesne et al. (2022) showing the complex sources and diffuse emission in Abell 3266 from the MWA.

2.1. *Surveys*

The GLEAM survey (Wayth et al. 2015; Hurley-Walker et al. 2017, 2019; Franzen et al. 2021) was the deepest widest area survey of the Southern sky at low frequencies. It covered all Declinations $<$ $+30$ deg over the frequency range of 72 to 231 MHz. This frequency range is divided into 5 subbands of 30.72 MHz each. The sensitivity ranges from approximately 6-10 mJy/beam, with beam sizes of a few arcminutes. The catalog contains over 300,000 sources[2].

The GLEAM-X survey will cover the same area and frequency coverage as GLEAM, however, it uses the MWA Phase II extended configuration, yielding higher angular resolution and lower noise. The resolution of GLEAM-X is closer to 1 arcminute, with sensitivity closer to 1 mJy/beam. The first data release is available with nearly 80,000 components in the catalog (Hurley-Walker et al. 2022). Figure 1 shows a comparison of the GLEAM and GLEAM-X data.

The MIDAS and GOLD surveys are planned as deep field Phase II surveys. MIDAS is deep pointings of 6 well-studied fields that would go 4 times deeper than GLEAM-X and aim for sub-mJy noise. While GOLD is focused on the single field of GAMA23, with an aim of 0.1 mJy/beam rms at 215 MHz.

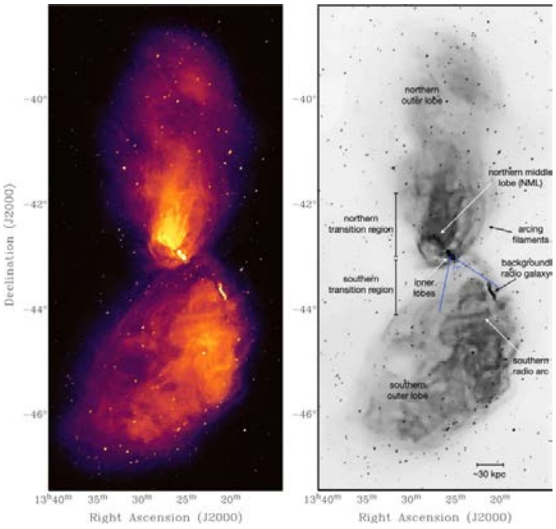

Fig. 3. Extended data Fig. 1 from McKinley et al. (2022) showing the MWA image of Centaurus A.

2.2. *Clusters and the Cosmic Web*

The short baselines of the MWA provide excellent sensitivity to large-scale diffuse emission, making it an ideal instrument to study the steep-spectrum emission associated with clusters and the cosmic web such as giant and mini radio halos, relics, and more.

In terms of the cosmic web, Vernstrom et al. (2017) used Phase I MWA data cross-correlated with galaxy number density maps to constrain magnetic field strengths from the synchrotron cosmic web. Hodgson et al. (2020) followed up possible higher-frequency detections of diffuse emission from filaments with the low-frequency and high-sensitivity of the MWA. Vernstrom et al. (2021) used MWA GLEAM data, as well as other low-frequency survey maps, in a stacking experiment to detect diffuse filament emission, finding a 3-σ excess of emission between cluster pairs.

There have a been a number of papers using the MWA to study galaxy clusters. Recently works like Duchesne et al. (2022) and Hodgson et al. (2021) report detections of ultra steep spectrum ($\alpha \leq -1.7$) cluster sources (see Fig. 2), with the “Jellyfish” source from Hodgson et al. (2021) being the steepest yet known at $\alpha = -6$. Duchesne et al. (2021b) looked at a sample of clusters with the MWA and the Australian SKA Pathfinder (ASKAP) and reported a double relic system in Abell 3186, a candidate halo in Abell 3399, a mini halo in RXC J0137.2-0912 and more. See additional cluster works such as Duchesne et al. (2021a,c).

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[2] Information about data access can be obtained from `https://www.mwatelescope.org/science/galactic-science/gleam/`

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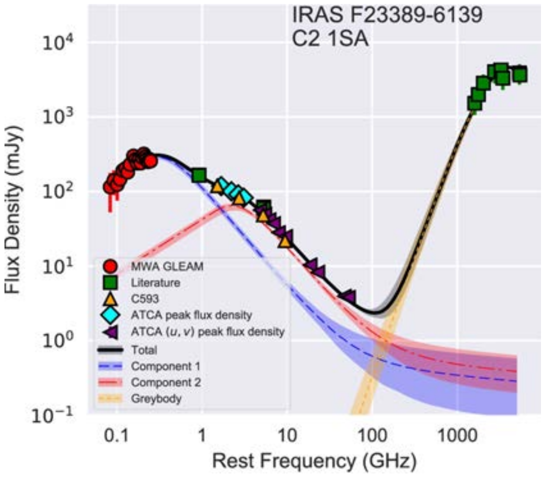

Fig. 4. Figure 1 from Galvin et al. (2018) showing the observed data and preferred SED modelling of IRAS F23389-6139.

2.3. *Radio Galaxies*

The MWA is a powerful instrument for studying galaxies, both active galactic nuclei (AGN) and star-forming galaxies, and the different stages of galaxy evolution. One particular area where the wide field of view and sensitivity to large-scale diffuse emission are useful is in studying large AGN, either nearby AGN or giant radio galaxies (GRGs). One recent example of this was McKinley et al. (2022), which presented a detailed view of Centaurus A (NGC 5128). This active galaxy is nearby such with the extended jet emission it covers nearly 8 deg on the sky (a difficult task to image such a large area for most other telescopes). The image can be seen in Fig. 3. Other MWA works on GRGS can be found in Seymour et al. (2020); Dabhade & Krishna (2022); Hurley-Walker et al. (2015). These works allow for the study of blackhole accretion in active galaxies, as well as possible evolutionary stages that create such large galaxies. White et al. (2020a) and White et al. (2020b) present details of the GLEAM 4-Jy sample, a detailed investigation into some of the brightest radio galaxies.

In terms of evolutionary stages of AGN, the low-frequency of the MWA is ideal for identifying remnant galaxies. The remnant phase of a radio galaxy begins once the jets switch off. These fossil radio galaxies are important for understanding the duty cycle of AGN and, when relaxed, are a good probe of surrounding pressures. Only looking at active radio galaxies does not offer a complete picture to the lifecycle of radio galaxies, due to a seemingly intermittent behaviour of the AGN jet activity. Quici et al. (2021) used MWA data, along with other higher-frequency data, to identify 10 new candidate remnant galaxies.

The large bandwidth of the MWA, and many subbands in the GLEAM survey, allow for detailed study of the spectra of galaxies. Galvin et al. (2018) used MWA data, along with other radio data, to study the spectrum between 70 MHz and 48 GHz for a sample of 19 starburst galaxies. This used the GLEAM data to constrain the curvature in a source SED and separate free-free absorption and synchrotron components, as is shown for one of the sources in Fig. 4. It was found that about 40% of the sample show spectral turnover at low-frequencies due to free-free absorption.

The recent works Ross et al. (2021) and Ross et al. (2022) looked at the spectral variability of low-frequency and peaked spectrum sources. Using the GLEAM data, these works found 323 sources with significant variability over year long timescales, and 51 of those had significant change in their spectral shape. For the peaked-spectrum sources, it was found the majority of the low-frequency variation was due to refractive interstellar scintillation.

2.4. *Polarimetry*

The POlarised GLEAM Survey (POGS, Riseley et al. 2018, 2020) is the linear polarisation survey complement of the GLEAM data. Rotation Measure (RM) synthesis was performed on all of the GLEAM sources, with additional source finding performed on the polarised intensity images. This work detected a total of 517 sources with 200 MHz linearly polarised flux densities between 9.9 mJy and 1.7 Jy, of which 33 are known radio pulsars (sky positions shown in Fig. 5). It is the largest-area catalogue of low-frequency ($< 300\,\mathrm{MHz}$) polarised sources. The wide bandwidth and low frequencies result in significantly smaller uncertainties for rotation measures. The extreme fractional bandwidth provided by such a sample will enable us to model the depolarisation behaviour over a broad λ^2 range to provide strong constraints on the magnetoionic structure of AGN lobes. It is planned for the polarisation to be processed along side the GLEAM-X Stokes I processing.

2.5. *Magellanic Clouds*

For et al. (2018) presented MWA study of both the large and small Magellanic clouds. They found the intensity of the radio continuum emission to be correlated with the HI column density, with this mainly coming from star-forming regions. The spectral indices across both the LMC and SMC are derived and shown in Fig. 6. The spectral indices show

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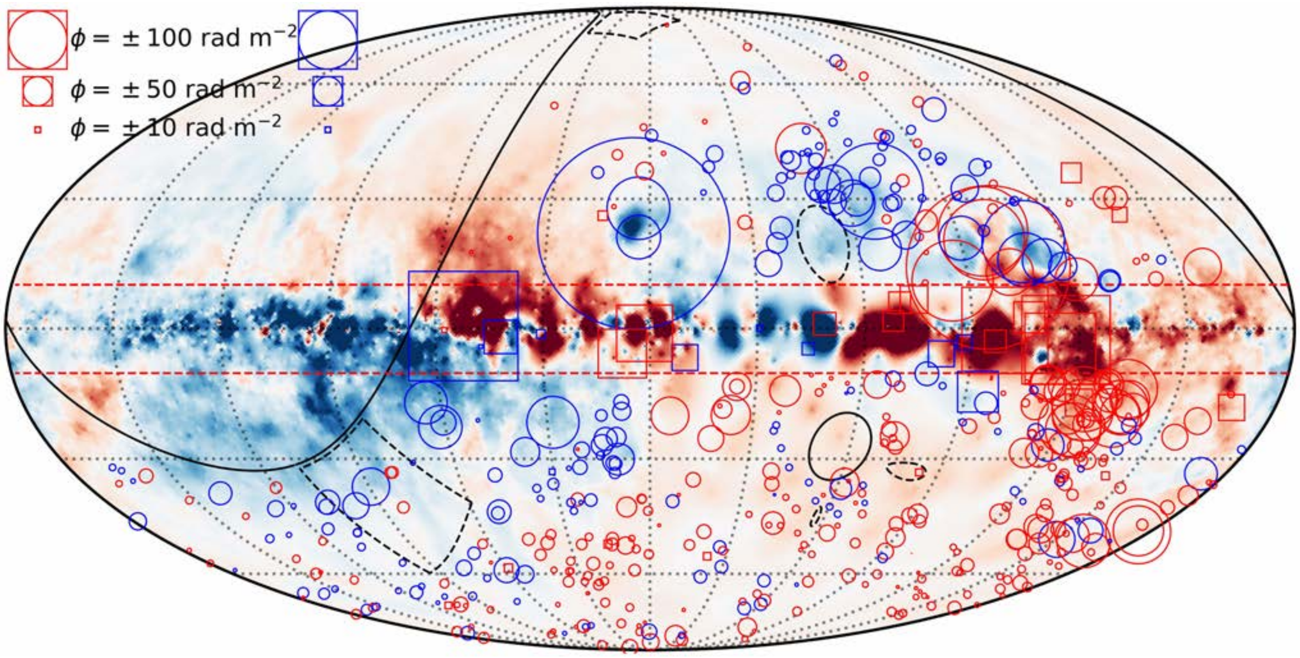

Fig. 5. Version of Fig. 1 from Riseley et al. (2020) showing the RM catalogue from the POGS survey.

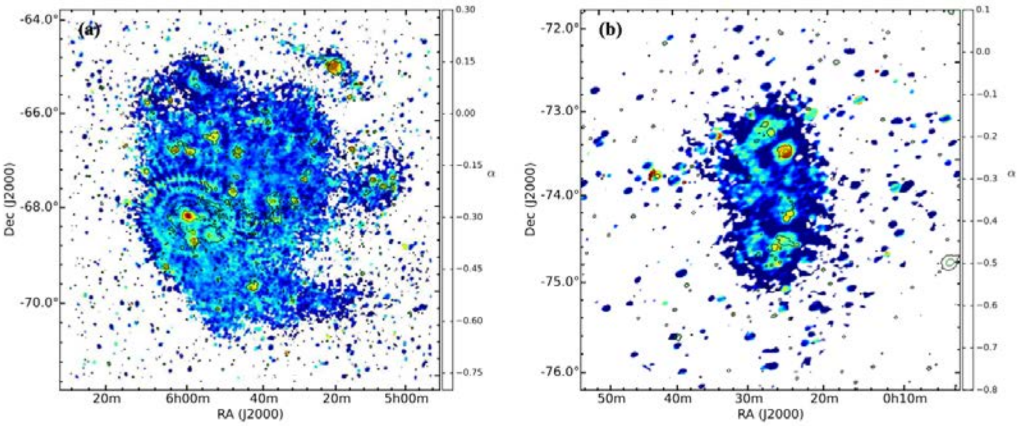

Fig. 6. From Fig. 7 of For et al. (2018) showing the spectral index maps of the large (left) and small (right) Magellanic clouds.

variation across the maps, reflecting the presence of both thermal and non-thermal components to the emission. The HII regions show flat spectral indices and strongly correlate with H_α.

3. CONCLUSIONS

The MWA has been incredibly successful instrument in Galactic and extragalactic science, as well as other areas. This is only likely to increase as it progresses into Phase III. It has opened the window to the low-frequency radio Southern sky. The low-frequencies and wide bandwidth enable spectral studies and identification of many sources such as radio remnants, GHz-peaked spectrum sources, cluster haloes and relics, and more. The large field of view, u, v coverage, and sensitivity to large angular scales make it ideal for studies of the cosmic web and Galactic emission. Many of the operational lessons learned will go on to inform the future SKA-low telescope. The MWA has helped to show the importance of low-frequency radio astronomy. The SKA-low will follow-on from the work of the MWA, however, there are many areas where other new instruments could provide new complementary data such as higher-resolution low-frequency array in the Southern hemisphere or instruments operating at the low to mid frequencies of $> 300\,\mathrm{MHz}$ and $< 1\,\mathrm{GHz}$.

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