

Science with the Murchison Widefield Array

Judd D. Bowman^{A,R}, David Kaplan^O, Tara Murphy^K, Divya Oberoi^F, Lister Staveley-Smith^N, Adam J. Burgasser^T, Iver Cairns^K, Shami Chatterjee^S, Lisa Harvey-Smith^C, Timothy Robishaw^K, Wayne Arcus^D, David G. Barnes^I, Gianni Bernardi^E, Frank H. Briggs^{B,Q}, John D. Bunton^C, Roger C. Cappallo^F, Brian E. Corey^F, Anthea Coster^F, Avinash Deshpande^H, Ludi deSouza^{B,K}, David Emrich^D, Philip Erickson^F, Robert F. Goke^F, Bryan M. Gaensler^{K,Q}, Lincoln J. Greenhill^E, Bryna J. Hazelton^M, David Herne^D, Jacqueline N. Hewitt^G, Melanie Johnston-Hollitt^P, Justin C. Kasper^E, Barton B. Kincaid^F, Ronald Koenig^C, Eric Kratzenberg^F, Colin J. Lonsdale^F, Mervin J. Lynch^D, S. Russell McWhirter^F, Daniel A. Mitchell^{E,J,Q}, Miguel F. Morales^M, Edward H. Morgan^G, Stephen M. Ord^D, Joseph Pathikulangara^C, Thiagaraj Prabu^H, Ronald A. Remillard^G, Alan E. E. Rogers^F, Anish A. Roshi^H, Joseph E. Salah^F, Robert J. Sault^J, N. Udaya Shankar^H, K. S. Srivani^H, Jamie B. Stevens^{C,L}, Ravi Subrahmanyan^{H,Q}, Steven J. Tingay^{D,Q}, Randall B. Wayth^{D,E,Q}, Mark Waterson^{B,D}, Rachel L. Webster^{J,Q}, Alan R. Whitney^F, Andrew J. Williams^N, Christopher L. Williams^G, and J. Stuart B. Wyithe^{J,Q}

^A Arizona State University, Tempe, AZ 85287, USA

^B Australian National University

^S Cornell University

^C CSIRO Astronomy and Space Science

^D Curtin University

^E Harvard-Smithsonian Center for Astrophysics

^F MIT Haystack Observatory

^G MIT Kavli Institute

^H Raman Research Institute

^I Swinburne University

^T University of California, San Diego

^J University of Melbourne

^K University of Sydney

^L University of Tasmania

^M University of Washington-Seattle

^N University of Western Australia

^O University of Wisconsin-Milwaukee

^P Victoria University of Wellington, New Zealand

^Q ARC Centre of Excellence for All-sky Astrophysics (CAASTRO)

^R Email: judd.bowman@asu.edu

Abstract: Significant new opportunities for astrophysics and cosmology have been identified at low radio frequencies. The Murchison Widefield Array is the first telescope in the Southern Hemisphere designed specifically to explore the low-frequency astronomical sky between 80 and 300 MHz with arcminute angular resolution and high survey efficiency. The telescope will enable new advances along four key science themes, including characterization of redshifted 21 cm emission from the Epoch of Reionization in the early Universe; solar, heliospheric, and ionospheric investigations of space weather; Galactic and extragalactic all-sky southern hemisphere surveys; and time-domain astrophysics. The Murchison Widefield Array is located in Western Australia at the site of the planned Square Kilometre Array (SKA) low-band telescope and is the only low-frequency SKA precursor facility. In this paper, we review the performance properties of the Murchison Widefield Array and describe its primary scientific objectives.

Keywords: cosmology: dark ages, reionization, first stars—instrumentation: interferometers—radio continuum: general—radio lines: general—sun: general

1 Introduction

The Murchison Widefield Array (MWA¹) is a low-frequency radio telescope operating between 80 and 300 MHz. It is located at the Murchison Radio-astronomy Observatory (MRO) in Western Australia, the planned site of the future Square Kilometre Array (SKA²) low-band telescope, and is one of three telescopes designated as a pathfinder for the SKA. The MWA has been developed by an international collaboration, including partners from the United States, India, Australia, and New Zealand. It is entering final construction and will be fully operational beginning in 2013. In this paper, we review the science capabilities of the telescope and the primary science objectives motivating its design and operation. Details on the technical design and specifications of the MWA are presented in a companion article (Tingay et al. 2012), which supercedes the earlier Lonsdale et al. (2009) description of plans for the instrument.

The four key science themes driving the MWA are: 1) detecting redshifted 21 cm emission from the Epoch of Reionization (EoR) in the early Universe, 2) solar, heliospheric, and ionospheric investigations of space weather, 3) Galactic and extragalactic surveys, and 4) time-domain astrophysics. We describe the plans and objectives for each of the key science themes in Sections 2 through 4.

The frequency range targeted by the MWA is one of the more difficult portions of the spectrum for ground-based radio telescopes due to strong distortions of incoming signals by the Earth's ionosphere and also due to congested terrestrial communications, including FM radio, TV stations, aircraft navigation, and satellite communications. Hence, the low-frequency radio sky remains one of the least explored domains in astronomy. The MRO site mitigates many issues associated with radio interference for the telescope, but processing of MWA observations requires particular care to correct for the ionospheric distortions.

The unifying design theme for the MWA is that of high survey efficiency. All of the science goals require large areas of the sky to be surveyed and the EoR objective further requires very very high surface brightness sensitivity. It was recognized early in the development of the MWA that arcminute angular resolution is a convenient balance between the opposing tensions of maximizing scientific returns and minimizing technical complexity. Arcminute angular scales are sufficient to probe typical ionized bubbles during the EoR, study diffuse and polarized emission structures in the Galaxy, reduce extragalactic source confusion, image bursts in the solar corona near the Sun's surface, and localize transient events with sufficient precision to allow follow-on searches at other wavelengths. In order to achieve arcminute resolution, the longest baseline of the MWA is 3 km. This distance is within the scale size of a typical isoplanatic patch in the ionosphere, allowing simplifying assumptions to be employed for widefield ionospheric calibration and keeping real-time imaging computations within reach of modest compute clusters.

Table 1: System parameters for MWA

Parameter	Symbol	^a Value
Number of tiles	N	128
Tile area (m ²)	A _{eff}	21.5
Total collecting area (m ²)		2752
Receiver temperature (K)	T _{rcv}	50
^b Typical sky temperature (K)	T _{sky}	350
Field of view (deg ²)	Ω _P	610
Frequency range (MHz)		80–300
Instantaneous bandwidth (MHz)	B	30.72
Spectral resolution (MHz)		0.04
Minimum baseline (m)		7.7
Maximum baseline (m)		2864

^aFor frequency-dependent parameters, listed values are given at 150 MHz

^bNijboer et al. (2009); Rogers & Bowman (2008)

The system properties of the MWA are described in detail in Tingay et al. (2012). We summarize them here in Table 1. The time needed to reach a point source sensitivity of σ_s for the MWA is given by:

$$t = \left(\frac{2k_B T}{A_{\text{eff}} N \epsilon_c} \right)^2 \frac{1}{\sigma_s^2 B n_p} \quad (1)$$

where k_B is the Boltzmann constant, $T = T_{\text{sky}} + T_{\text{rcv}}$ is the system temperature, A_{eff} is the effective area of each antenna tile, N is the number of antenna tiles, ϵ_c is the correlator efficiency, B is the instantaneous bandwidth, and n_p is the number of polarizations. For full-bandwidth (30.72 MHz) continuum imaging at 150 MHz, this reduces to $t \approx 8 \times 10^4 / (B \sigma_s^2)$ seconds for σ_s in units of Jansky. The intrinsic source confusion limit is estimated to be $\sim 10 - 20$ mJy at 150 MHz for the MWA angular resolution of $\sim 1 - 5'$ (Windhorst et al. 1985). Hence, the MWA will reach the confusion limit in ~ 10 seconds for continuum imaging or within a few hours in a single 40 kHz spectral channel.

The surface brightness sensitivity of the MWA varies significantly with angular scale. The MWA antenna layout emphasizes a dense, central core in order to achieve a high surface brightness sensitivity on degree-scales for EoR science. For a typical EoR spectral resolution of 1 MHz, the brightness temperature uncertainty is less than 150 mK after 1 hour of integration on degree-scales, whereas it is approximately 3 K on arcminute-scales.

In the remainder of the paper, we discuss the four key science themes. Section 2 describes the Epoch of Reionization science. In Section 3, broad categories of radio astronomy science are discussed within the context of sky surveys. Section 4 describes the time-domain astronomy that will be possible with the MWA and Section 5 presents the primary solar, heliospheric, and ionospheric goals. We conclude in Section 6.

¹<http://mwatelescope.org>

²<http://skatelescope.org>

2 Epoch of Reionization

One of the most significant events in the history of the intergalactic medium (IGM) was the reionization of hydrogen. The epoch of reionization (EoR) marks the time when the small fraction of matter within galaxies significantly affected their surroundings (and hence future generations of galaxies), ionizing the intergalactic gas and heating it from 10s of Kelvin to $\sim 10^4$ K.

The MWA has been designed with the goal of detecting 21 cm emission from the reionization epoch. The 21 cm hyperfine transition line of neutral hydrogen is anticipated to provide an ideal probe of reionization. Its weak oscillator strength (in contrast to the Ly- α line) allows 21 cm photons to propagate from fully neutral environments at high redshifts without appreciable absorption. This property makes it possible to directly observe the neutral hydrogen gas before and during reionization.

Unlike the continuum emission of the cosmic microwave background (CMB), 21 cm emission contains information in the frequency (or redshift) dimension in addition to in angle, enabling the study of the full history of reionization. Redshifted 21 cm emission from neutral hydrogen gas in the IGM should appear as a faint, diffuse background in radio frequencies below $\nu \lesssim 200$ MHz for redshifts above $z > 6$, where $\nu = 1420/(1+z)$ MHz. At these redshifts, the expected unpolarized differential brightness temperature of the redshifted 21 cm line relative to the CMB is readily calculable from basic principles (see Furlanetto et al. 2006, for a complete review) and is given by

$$\delta T_{21}(\vec{\theta}, z) \approx 25 x_{HI} (1 + \delta) \left(\frac{1+z}{10} \right)^{1/2} \times \left[1 - \frac{T_\gamma(z)}{T_S} \right] \left[\frac{H(z)/(1+z)}{dv_{\parallel}/dr_{\parallel}} \right] \text{mK}, \quad (2)$$

where x_{HI} is the neutral fraction of hydrogen, δ is the local over-density in baryons, $T_\gamma(z) = 2.73 (1+z)$ K is the temperature of CMB at the redshift of interest, T_S is the spin temperature that describes the relative population of the ground and excited states of the 21 cm transition, $H(z)$ is the Hubble constant, and $dv_{\parallel}/dr_{\parallel}$ is the velocity gradient along the line of sight.

All of these factors contain unique astrophysical information. The dependence on δ traces the development of the cosmic web (Scott & Rees 1990), while the velocity factor sources line-of-sight distortions that can be used to separate different components of the signal (Barkana & Loeb 2005). The other two factors depend on the ambient radiation fields in the early Universe. The local neutral fraction, x_{HI} , is determined by the ionizing radiation emitted by galaxies and possibly quasars. Theoretical studies suggest that the distribution of neutral gas during reionization is very inhomogeneous (e.g. McQuinn et al. 2007). Finally, the 21 cm spin temperature, T_S , is determined primarily by three mechanisms that affect the hyperfine level populations: The ambient radiation at 21 cm set the CMB with T_γ , the ultraviolet background that tends to drive T_S to the gas temperature (Wouthuysen 1952; Field 1958), and heating from the cosmological

X-ray background (Chen & Miralda-Escudé 2004). By the time the Universe is a few percent ionized, most calculations predict that $T_S \gg T_\gamma$, such that fluctuations in T_S are not important (e.g. Furlanetto et al. 2006).

Figure 1 illustrates how the factors in Equation 2 combine to create the observable 21 cm signal. The panels in this figure are from the simulations of McQuinn et al. (2007) and are 100 comoving Mpc across or $\sim 0.5^\circ$ in angle (a small fraction of the $\sim 20^\circ$ MWA field of view). The left panel of Figure 1 shows the expected signal just before reionization begins, when the fluctuations are dominated by local perturbations in the matter density. In the middle panel, reionization is underway ($x_{HI} \approx 0.5$), and the large-scale voids in the map signify ionized regions. After reionization has largely finished (right panel), only localized pockets of neutral hydrogen remain.

The MWA will attempt to probe structures in the redshifted 21 cm background in order to reveal the astrophysics of reionization. The MWA is expected to be sensitive to the power spectrum of the 21cm signal between the redshifts of $6 < z \lesssim 10$ (Section 2.1). Its observations have the potential to characterize the nature of the sources that are responsible for ionizing the IGM, chart the evolution of the global neutral fraction, and probe the nature of quasar emissions by constraining the properties of their ionized proximity zones.

2.1 21 cm Power Spectrum

Initial MWA observations aimed at detecting 21 cm emission will focus on two target fields at relatively high Galactic latitudes (see Figure 3). Over the course of one year, approximately 1000 hours of optimal night-time observations will be divided between these two fields. The signal-to-noise ratio (S/N) in each pixel will be $\lesssim 1$, with the highest S/N on the largest angular modes. Hence, rather than imaging the 21 cm brightness temperature in the target fields, reionization science with the MWA will focus on statistical measures of the 21 cm emission. The number of independent measurements in a raw, multi-frequency MWA data cube will be $\sim 10^8$. These samples record largely Galactic synchrotron and free-free emission ($\gtrsim 200$ K) and extragalactic continuum sources (~ 50 K), with only a small contribution from the redshifted 21 cm signal (~ 25 mK). The primary approach planned for the MWA is to calculate the power spectrum of spatial fluctuations of the 21 cm signal.

The three-dimensional power spectrum of redshifted 21 cm emission is the square of the Fourier transform of δT_{21} (Eq. 2). It has a large spherically-symmetric component due to the isotropy of space, but has slightly more power for modes that point in the line-of-sight direction that results from peculiar velocities. The predicted components in the full three-dimensional power spectrum can be decomposed into terms with different powers of $\mu \equiv \hat{k} \cdot \hat{n}$, where μ is the cosine of the angle between the line of sight and the wavevector (Kaiser 1987; Barkana & Loeb 2005;

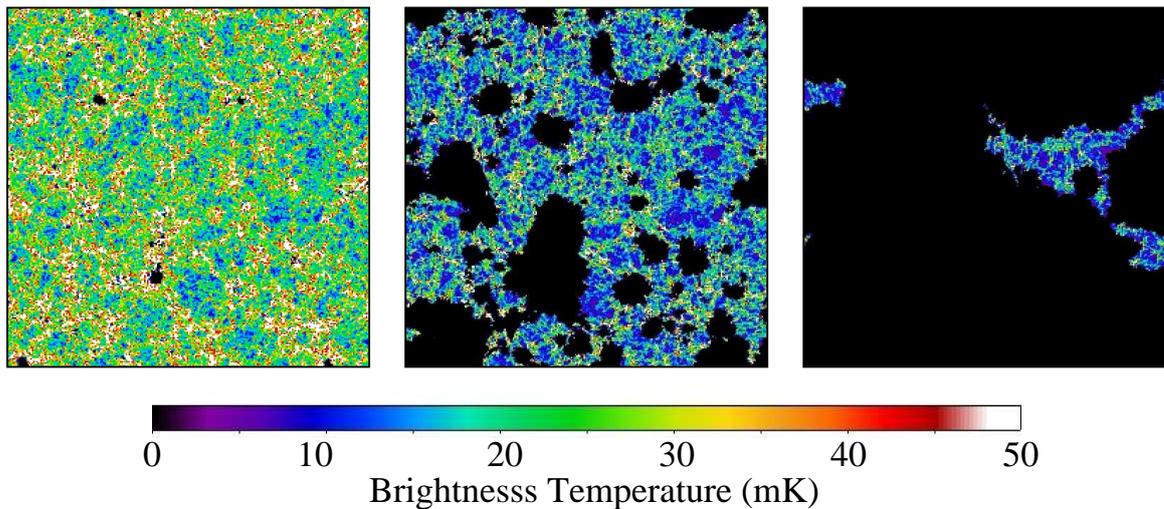


Figure 1: Simulated 21 cm brightness temperature maps from simulation S1 in McQuinn et al. (2007) at three epochs calculated under the assumption that $T_S \gg T_\gamma$. The left panel is an almost fully neutral IGM (before reionization at $z = 12$) such that the 21cm emission traces the matter density. The middle panel is during reionization ($x_{HI} \approx 0.5$, which occurs at $z = 8$ in this simulation): The dark regions represent ionized regions around galaxies. Lastly, the right panel shows the residual emission near the end of reionization ($z = 6$). Each panel is 100 comoving Mpc across and subtends 0.5° (a small fraction of the MWA field of view).

McQuinn et al. 2006). Thus,

$$P_{21}(\vec{k}) = P_{\mu^0}(k) + \mu^2 P_{\mu^2}(k) + \mu^4 P_{\mu^4}(k). \quad (3)$$

During reionization, the P_{μ^0} term typically dominates, and the most important contribution to P_{μ^0} is the fluctuations in the neutral fraction (McQuinn et al. 2006).

Averaging $P_{21}(\vec{k})$ over angle to yield $P_{21}(k)$ loses some statistical information, but at the sensitivity of MWA this loss is minor during reionization. With one year of the planned observing program, the MWA can constrain $P_{21}(k)$ at a given redshift and across a range of scales spanning $0.01 \lesssim k \lesssim 1$ comoving Mpc^{-1} with total $S/N \approx 14$ [TBD: Cite Beardsley paper when published] (Morales & Hewitt 2004; Bowman et al. 2006; McQuinn et al. 2006). The sensitivity of the MWA to the spherically-averaged power spectrum is shown in the right panel of Figure 2.

The properties of the power spectrum of $P_{21}(k)$ during reionization are dominated by the characteristics of the ionized bubbles (Figure 1, middle panel) that are determined by the ionizing radiation produced by the first galaxies and quasars. The left panel of Figure 2 illustrates how $\Delta_{21} \equiv (k^3 P_{21}(k)/2\pi^2)^{1/2}$ contains information about the reionization process. It plots Δ_{21} for the fiducial model of Lidz et al. (2008) at several neutral fractions and the corresponding redshifts. The shape of the power spectrum evolves considerably as the hydrogen in the IGM becomes ionized, with power shifting from small scales initially, to larger scales later when large ionized bubbles have formed. Eventually, the amplitude decreases as hydrogen reionization completes.

The sensitivity forecasts shown in the right panel in Figure 2 utilize both the primary and secondary target fields in combination, assuming that each field has been observed over an 8 MHz bandwidth (corresponding to $\Delta z \approx 0.5$). The full 32 MHz instantaneous bandwidth of the MWA will automatically yield four such measurements spanning a contiguous redshift range of $\Delta z \approx 2$. Initial observations will focus on the lower redshifts ($6 < z < 8$), where the sensitivity of the instrument is highest due to the lower sky temperature. Observations at low redshifts will crucially demonstrate whether the foreground subtraction is successful, since the quality of the foreground subtraction will be readily apparent at $z < 6$ (where no 21 cm signal should be detectable by the MWA since $x_{HI} \lesssim 2\%$ after reionization (Wyithe & Loeb 2008)).

2.1.1 Sources of Reionization

The 21 cm sky contains a wealth of information about the properties of the ionizing sources because they strongly affect the topology of the EoR. Reionization scenarios dominated by stars in galaxies produce well-defined ionized regions, while “miniquasars” (small accreting black holes) yield more diffuse features (Zaroubi & Silk 2005) and reionization processes involving decaying/annihilating dark matter particles would be very inhomogeneous (Belikov & Hooper 2009). The 21 cm observations could even distinguish between different stellar reionization scenarios (Lidz et al. 2008). For example, more massive galaxies produce larger ionized regions (Furlanetto et al. 2004; McQuinn et al. 2007). If it is able to constrain the shape and evolution of the

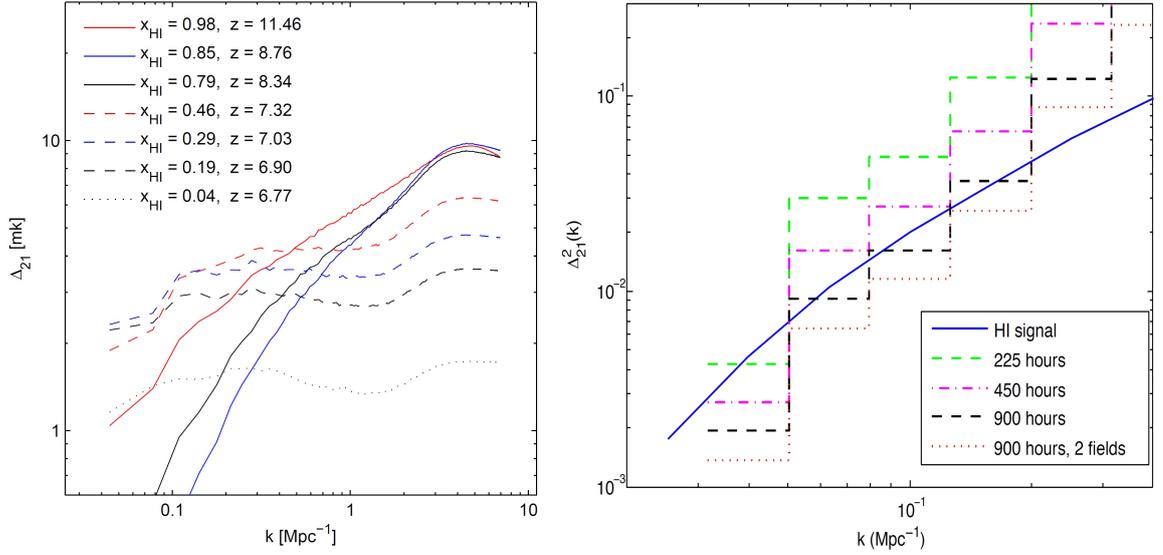


Figure 2: [TBD: The right panel is a placeholder for 128T from Adam] *Left:* Simulated three-dimensional 21 cm power spectra averaged over spherical bins and plotted as $\Delta_{21} \equiv (k^3 P_{21}/2\pi^2)^{1/2}$. These curves are calculated using the fiducial simulation described in Lidz et al. (2008), neglecting redshift-space distortions and in the limit $T_S \gg T_\gamma$. The power spectra are plotted for different neutral fractions (and redshifts). The slope of the power spectrum is very steep at the beginning of reionization ($x_{\text{HI}} \gtrsim 0.8$), but flattens quickly once large ionized regions have formed by $x_{\text{HI}} \approx 0.5$. At the end of reionization ($x_{\text{HI}} \lesssim 0.5$), the amplitude of the power spectrum decreases with decreasing neutral fraction. *Right:* Sensitivity of the MWA to the 21 cm power spectrum in the limit that thermal noise and sample variance dominate the uncertainty. In this case, the IGM is assumed to be fully neutral at $z = 8$, and the noise is modeled for a combined observation of the primary and secondary target fields, each with 300 hours of integration. Note that the signal is predicted to be larger when ionized regions are present. Approximate trends derived from the simulations of Bowman et al. (2009) for the total thermal noise power and the diffuse synchrotron foreground power are also shown for comparison. Under ideal instrumental calibration, subtraction of diffuse foregrounds contributes little additional uncertainty (see Section 2.4).

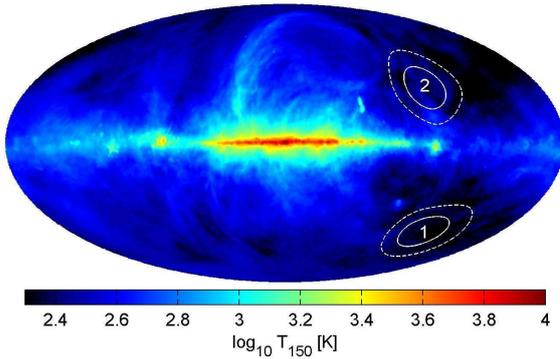


Figure 3: Projected all-sky brightness temperature map of de Oliveira-Costa et al. (2008) at 150 MHz. The primary (1) and secondary (2) target fields for EoR observations are centered at $\alpha, \delta = 60^\circ, -30^\circ$ ($\ell, b = 228^\circ, -49^\circ$) and $\alpha, \delta = 155^\circ, -10^\circ$ ($\ell, b = 253^\circ, 38^\circ$), respectively. The solid white curves indicate the 50% response power contour of the primary antenna tile beams and the dashed lines show the 10% power contour.

power spectrum, the MWA will reveal the nature of some of the first cosmological objects.

2.1.2 The Neutral Fraction

Existing observations have provided tantalizing hints about reionization, but even more unanswered questions. CMB observations find that the average redshift of reionization is $z = 10 \pm 2$ (Komatsu et al. 2009), and quasar absorption spectrum imply that the universe was totally ionized by $z = 6$, one billion years after the Big Bang. In addition, several studies have interpreted the large saturated regions at $z > 6$ in these absorption spectra as evidence for the end of reionization (e.g., Fan et al. 2006), but this conclusion is disputed.

Detection of the 21 cm power spectrum will yield measures of $\bar{x}_{HI}(z)$ through predictable features that depend on the neutral fraction. As evident in Figure 2, the intensity of 10 comoving Mpc-scale fluctuations in 21 cm brightness temperature briefly fades when reionization begins and the first galaxies ionize the overdense regions within a couple comoving Mpc of them. Next, the ionized regions surrounding individual galaxies overlap, creating ~ 10 comoving Mpc ionized regions and an increase in power on these scales. Finally, all of the fluctuations fade as these bubbles overlap, swallowing the neutral hydrogen that remains. Each of these trends can be used to disentangle $\bar{x}_{HI}(z)$.

For many possible sources that have been considered in the literature (such as galaxies, quasars, and mini-halos), the amplitude of the power spectrum peaks at $\bar{x}_{HI} \approx 50\%$. The MWA could probe the global ionization history by tracking the evolution of this amplitude and shape of the 21 cm power spectrum. Using these features, the volume filling factor of neutral

hydrogen (comparable to the mass-averaged neutral fractional) can be constrained after two years of observations to between $0.4 < x_{HI} < 0.75$ at 2σ significance [TBD: Check with Adam to get 128T numbers] for the redshift where the power spectrum achieves its maximum amplitude (Lidz et al. 2008). While unlikely, it is possible that the IGM is highly ionized over the range of redshifts measured by the MWA. Lidz et al. (2008) found that a null detection with the MWA at $z \leq 8$ would be able to constrain the neutral fraction to $\lesssim 4\%$ at more than 3σ .

Observations of individual quasar HII regions offer an additional probe of the global neutral hydrogen fraction since the contrast between the ionized HII region and neutral IGM can provide a measurement of the neutral fraction at the redshift of the quasar. Geil et al. (2008) have found that the shape of the quasar HII regions can be recovered from foreground subtracted MWA maps by using the entire data cube to help determined the contrast between the external IGM and ionized interior.

2.2 Quasar HII Regions

The detection of large quasar-generated HII regions in redshifted 21 cm emission late in the epoch of reionization may be possible with the MWA (Wyithe et al. 2005; Wyithe 2008). Geil et al. (2008) have modeled the observation of quasar HII regions in a partially ionized IGM. Figure 4 shows a simulated example of a recovered quasar HII region with the MWA with 100 hours [TBD: I think the performance of 128T will be just as good, but it will need 400 hours instead of 100] of integration. The recovery is possible only for quasars with positions known *a priori*. Although the MWA fields will not overlap the Sloan Digital Sky Survey (SDSS) fields, where the existing known $z \approx 6$ quasars reside, the contemporaneous Sky Mapper optical survey (Keller et al. 2007) should find around one quasar at $z > 6.25$, and around 5 quasars at $z > 6$ per MWA field.

Like all 21 cm signatures of the reionization era, the detection of a quasar HII region will need to overcome the difficulties associated with the removal of bright Galactic and extragalactic foregrounds. Geil et al. (2008) find the primary effect of continuum foreground removal is to erase contrast in the image. In particular, contributions to the 21 cm intensity fluctuations that have a scale length comparable to the frequency bandpass of the observation are removed by foreground subtraction. This loss of contrast, however, does not severely affect the ability of 21 cm observations to measure the size and shape of the HII region. To demonstrate this quantitatively, Geil et al. (2008) modeled the HII region shape as a spheroid described by six parameters and showed that the shape recovered following foreground removal agrees well with the shape derived directly from fitting using the input HII region model.

Using the recovered best-fit shape of the HII region, the global neutral fraction of hydrogen in the IGM can be measured directly from the contrast in intensity between regions that are within and beyond the

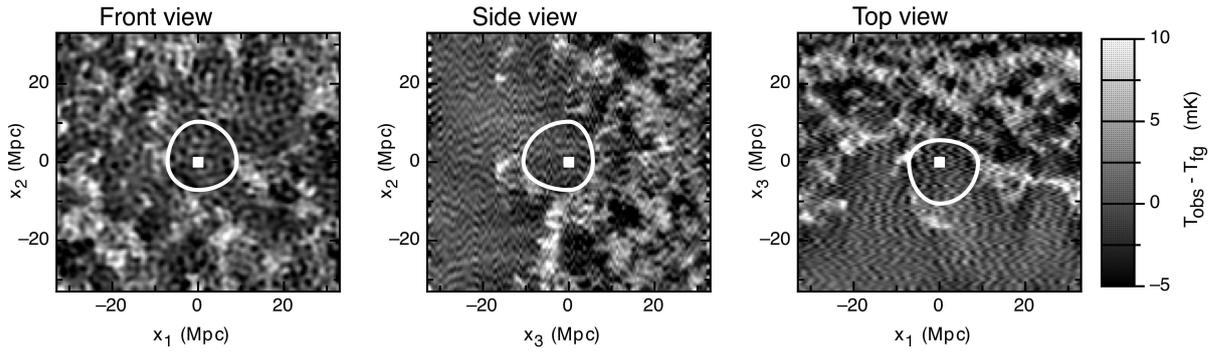


Figure 4: Simulated recovery of a quasar HII region in an evolving IGM, as observed by an MWA-like instrument with four times the collecting area of the MWA using 100 hours of integration, equivalent to 400 hours of integration with the MWA (Geil et al. 2008). Observed maps following diffuse continuum foreground removal are shown. The data cube is only a small part of a full MWA field and spans ~ 3.3 degrees on a side and 33 MHz deep. The three panels show different slices through the center of the box when viewed from the front, side, and top. Each slice is 6 Mpc thick, which corresponds to ~ 3 MHz along the x_3 -axis. The extracted shape of the HII region is shown, based on a 9 parameter model. The quasar was assumed to have $R = 34$ comoving Mpc and a lifetime of 4×10^7 years centered on $z = 6.65$, which is also the redshift at the center of the simulation box. The mass-averaged IGM neutral fraction at the redshift of the quasar is $\approx 15\%$.

HII region. However, since foreground removal lowers the observed contrast between the HII region and the IGM, such a measurement of the neutral fraction would require a correction factor. The value of this correction factor depends on the reionization history and the polynomial used for foreground subtraction, and must be estimated using astrophysical models.

2.3 Non-Gaussian Statistics

During the reionization epoch, fluctuations in the 21 cm emission are expected to be highly non-Gaussian due to galaxy bias and the patchy structure imparted by the ionized bubbles in the IGM. The power spectrum (or two-point correlation function), therefore, is not a sufficient descriptor of the properties of the field, and additional statistical measures can provide complementary information. Several extensions to the power spectrum have been proposed in this context, including direct measures of the one-point probability distribution function (PDF) or its third moment (skewness), the three-point correlation function (bispectrum), and derived metrics such as the PDF of the difference in 21 cm brightness temperature between two points.

2.4 Foreground Subtraction

The ability of the MWA to achieve its reionization science is entirely contingent on the successful separation of the 21 cm signal from astrophysical foregrounds. Hence, developing and demonstrating the techniques required to subtract foregrounds is a critical research objective. The baseline foreground subtraction strategy is a multi-stage process consisting of the following principal stages:

1 - Bright source subtraction. The first step in foreground subtraction is the removal of bright point sources (e.g. extragalactic AGN). This is necessary because the sidelobes of these sources mask the 21 cm signal. Recent theoretical studies have indicated that bright point source subtraction must be complete for sources with flux greater than $S \gtrsim 100$ mJy in order to allow for successful subsequent Galactic continuum foreground subtraction (Liu et al. 2009). The brightest sources in the field will be “peeled” (self-calibrate and subtract) from the raw visibility measurements (Mitchell et al. 2008). Efficient techniques to remove point sources from gridded and integrated “base maps” are also under investigation.

2 - Diffuse continuum subtraction. A variety of mechanisms contribute to diffuse continuum emission in the low-frequency radio sky including Galactic synchrotron emission, Galactic free-free emission, extragalactic free-free emission, and a sea of faint extragalactic point sources that are too numerous to identify individually in base maps and are, thus, said to be “confused”. All of these foregrounds are significantly stronger than the redshifted 21 cm signal and have considerable angular structure on the sky (see Figure 2 and Santos et al. 2005, their Figure 5). But the emission mechanisms of these foregrounds produce smooth spectra that follow power-law profiles, making them possible to separate from the redshifted 21 cm emission by their long spectral coherence scales compared to the small, ~ 1 MHz spectral coherence of the reionization signal. A variety of techniques have been proposed to accomplish this separation including polynomial fits along the spectral axis of each pixel in a base map or its uv-map conjugate, Minkowsky-functionals, and non-parametric techniques. The baseline approach planned for the MWA is to fit and sub-

tract a third-order polynomial from each pixel in the uv-domain representations of the bright source cleaned base maps. This technique has been demonstrated for the MWA in the limit of perfect instrumental calibration (Bowman et al. 2009; Liu et al. 2009,?).

3 - Polarized leakage subtraction. In addition to the foreground issues discussed thus far, gain and phase calibration errors and non-ideal feeds conspire to contaminate all Stokes parameters further. This leakage leads to some portion of the complex linear polarization signal finding its way into the Stokes I intensity maps that will be used for the redshifted 21 cm measurements. By exploiting the Fourier relationship between the polarized signal and the Faraday dispersion function, it is possible to identify components of polarized signal with specific Faraday depth. This process is known as rotation measure (RM) synthesis. The three-dimensional Stokes I data set is first re-sampled along the frequency axis into the natural λ^2 -basis for Faraday rotated emission. A one-dimensional Fourier transform is then applied along each line of sight. Any feature observed with a non-zero Faraday depth in the three-dimensional RM synthesis map will, by definition, be polarized contamination. By applying an inversion process together with knowledge of the instrument's specific leakage behavior, this contamination can be subtracted. Conceptually, this stage is very similar in nature to the continuum subtraction stage that precedes it, with the addition of a basis change.

4 - Statistical template fitting. The completion of the above three foregrounds subtraction stages yields the final foreground-cleaned maps. Many classes of errors and residuals remaining in the foreground-cleaned maps can be modeled given sufficient knowledge of the instrumental response (Morales et al. 2006; Bowman et al. 2009; Datta et al. 2010; Morales et al. 2012). The statistical properties of these residuals can be exploited to provide an additional layer of foreground removal by fitting templates of the residual statistical structures during the final redshifted 21 cm power spectrum parameter estimation. This technique is now commonly employed in CMB power spectrum analysis to account for the angular power of faint point sources and the effects of gravitational lensing.

3 Galactic and Extragalactic Science

The MWA offers several exciting science opportunities under the collective banner ‘‘Galactic and Extragalactic’’ science. The major input into this science comes from a deep (confusion-limited) all-sky survey over the MWA frequency range with full polarimetry and spectral resolution. This survey is a critical undertaking as it will also be used by the other science programs as a basis for an all-sky foreground model and the identification of calibrators. The data will also be combined with other new surveys such as the GALFACTS (1.4 GHz), S-PASS (2.4 GHz) and Planck (27 GHz to 1 THz) surveys.

The following sections describe a selection of Galactic and extragalactic experiments for which the MWA

is well suited. These projects capitalize on three advantages of the MWA’s low observing frequencies: (1) non-thermal sources will be very bright; (2) Faraday rotation and depolarization will be very strong; and (3) along some sightlines free-free absorption will be significant.

3.1 The Cosmic Web at Low Frequencies

Theory suggests that the infall of baryons into the cosmic web results in high Mach number intergalactic shocks. When combined with seed magnetic fields, efficient cosmic ray acceleration is possible, resulting in steep-spectrum synchrotron emission (Keshet et al. 2004). This may be a ubiquitous component of the extragalactic radio sky, and is related in origin to large-scale shocks already seen in colliding clusters of galaxies. The MWAs centrally condensed antenna configuration provides the theoretical sensitivity that appears to be required to make the maps of this relativistic cosmic web. However, the accurate subtraction of discrete sources requires long baselines and high image fidelity. This may limit the detectability to the densest portions of the web.

3.2 Radio Relics and Clusters

The MWA is well suited for studying the diffuse, steep-spectrum emission from clusters of galaxies and the so-called ‘radio relics’. These objects are probes of relativistic electrons and large-scale magnetic fields in the largest virialised structures in the Universe (Ferrari 2008). The relics appear to be due to injection of cosmic rays from active galactic nuclei (AGN) that have since ceased to be active. However, the central cluster emission appears related to the intergalactic shocks discussed above, but on scales and at densities associated with clusters. Mechanisms for accelerating the cosmic ray electrons responsible for this emission are turbulent amplification (Petrosian 2001) and hadronic collisions (Pfrommer et al. 2008), perhaps associated with cluster mergers.

3.3 Faraday Tomography and Magnetic Fields

The Milky Way and most other spiral galaxies all show well-organized, large-scale magnetic fields, but the processes that amplify and maintain these fields are still not understood. On smaller scales, fluctuations in these magnetic fields regulate the dissipation of large-scale gas flows via a turbulent cascade. However, it is as yet unclear what processes generate turbulence in the interstellar medium (ISM), and how the subsequent spectrum and outer scale of turbulence depend on the surrounding conditions. Polarized radio waves experience Faraday rotation when they propagate through a magnetized plasma. The amount of rotation depends on the square of the wavelength, and on the path integral of $n_e B$ along the line of sight (where n_e is the electron density of the ISM, and B is

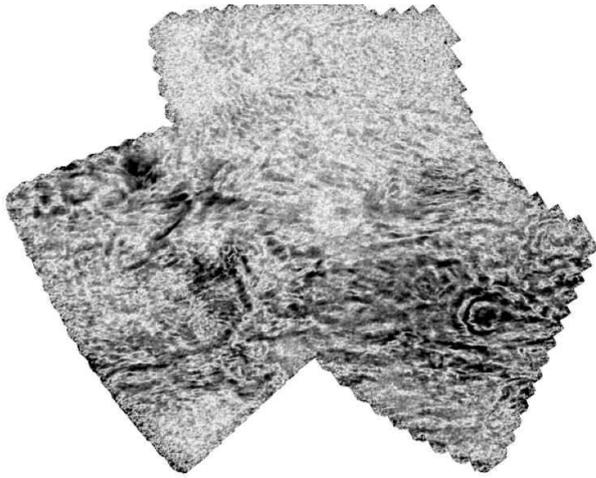


Figure 5: Polarized intensity at 300 MHz, from the Westerbork Northern Sky Survey Schnitzler et al. (2007), at a resolution of 7 arcmin. The field extends from the Galactic Plane up to mid-latitudes, and demonstrates the presence of complex polarized emission with no counterpart in total intensity. The spatial structure in polarization, along with the frequency dependence of this polarization along each sightline, can be used to determine the properties of both ordered and turbulent magnetic fields in the Milky Way's ISM.

the magnetic field strength). By exploiting this phenomenon, the MWA can provide a stunning new view of the large- and small-scale properties of otherwise unobservable magnetic fields in the Milky Way.

At the low observing frequencies of the MWA, small rotation measures (RMs) have substantial effects on the distribution of polarized emission from the sky. An example is provided in Fig. 5, which shows the complicated polarization pattern seen at 300 MHz in a typical patch of the sky. This emission directly traces invisible foreground magnetic fields, which imprint their structure on the smooth polarized synchrotron emission from the Milky Way via foreground Faraday rotation. By imaging the polarized sky at a range of frequencies, the MWA will provide direct measurements of the turbulent cascade in the local interstellar medium, and will reveal the detailed magnetic geometries of discrete large-scale structures such as the Local Bubble, the North Polar Spur and the Magellanic Clouds. Using the high spectral resolution of the MWA, we can also apply 'RM synthesis' techniques (Brentjens & de Bruyn 2005) to the data, in which the distribution of polarization angle vs. wavelength-squared along each sightline is Fourier transformed to isolate overlapping RM components. This will provide a unique tomographic view of magneto-ionized gas, allowing the identification of multiple emitting and rotating regions along the same line of sight.

The MWA is expected to make the largest contributions to Galactic science by observing at mid-

and high-latitude regions. Depolarisation is already severe in the inner Galactic plane at 1.4 GHz (??), and it is likely that most of the inner Galactic plane will be completely depolarised at 300 MHz. However, regions at mid and high latitudes show considerable diffuse Galactic polarised structure at 350 MHz (??). MWA's high sensitivity for extended structure will be able to map the diffuse polarised emission down to very low intensities, thus making visible weak Galactic magnetic fields in the local interstellar medium and Galactic extended disk and halo that are undetectable at higher frequencies. RM synthesis across the entire MWA frequency band will result in a RM resolution of 0.3 rad m^{-2} , which gives unprecedented detail in RM structure, allowing detailed studies of e.g. interstellar magnetised turbulence, or magnetism in old supernova remnants. Increasing depolarisation as a function of decreasing frequency will give independent measurements of the amount and scale of fluctuations in the magneto-ionised medium (?).

Rotation measures from extragalactic polarised point sources can be used to probe the intervening medium between the source and the observer, where generally the Galactic RM component dominates. Little is known about the polarisation percentages of extragalactic point sources at low frequencies. At 1.4 GHz, the expected number of linearly polarised sources down to a 3σ sensitivity of 1 mJy is about 1.2×10^4 per steradian (?). Although synchrotron power increases with wavelength, so that more synchrotron sources will be visible at low frequencies, the number of polarised sources is expected to decrease at low frequencies due to increased internal depolarisation.

Extragalactic point source RMs will provide a "RM Grid" (?) that can be used to model large-scale magnetic fields in the Milky Way, and, if the RM grid is dense enough, in nearby galaxies. Provided that polarisation calibration is accurate enough, the MWA will observe point source RM values with superb precision, which may even allow studies of magnetic fields in clusters and/or the intergalactic medium.

3.4 The Magellanic Clouds

The Magellanic System, consisting of the LMC, SMC and other components such as the Magellanic Stream, Bridge and Leading Arm is the Milky Way's most significant neighbour. The Clouds and the Milky Way are engaged in a three-body interaction allowing us to study at close hand the effect of dynamical interaction processes on the physical structure, star-formation, magnetic fields and chemistry of such galaxies at close hand. The location of the Clouds in the deep southern sky makes them ideal candidates to observe with the MWA in preparation for much more detailed studies at similar frequencies with the SKA.

A comparison of radio and far-infrared emission in the Magellanic Clouds and other nearby galaxies allows for a more detailed study of the correlation of cosmic rays, magnetic fields and star-formation than is possible for distant galaxies. At GHz frequencies, ATCA and IRAS studies (see Fig. 6) allowed Hughes et al. (2006) to find that the radio/far-infrared (FIR)

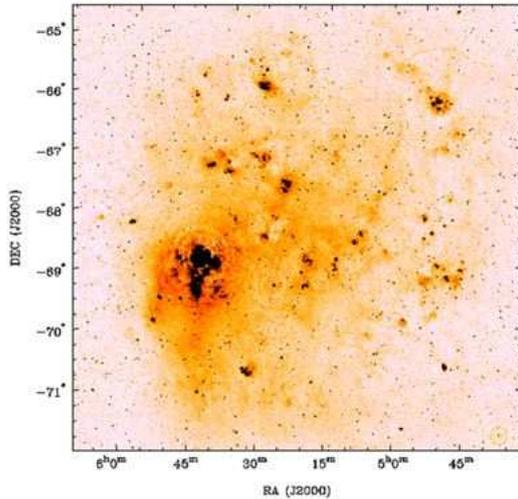


Figure 6: Radio continuum from the LMC at 1.4 GHz; Parkes/ATCA data (Hughes et al 2007).

relation breaks down at ~ 50 pc (3 arcmin). Residual correlation at smaller scales remains due to the thermal component of the radio emission. Low-frequency observations of 6C galaxies have shown that the radio/FIR correlation remains good at 151 MHz (Fitt et al. 1988). Such observations are useful for further separating thermal and non-thermal sources of emission, for the study of synchrotron spectral aging and cosmic ray diffusion, and for allowing k-corrections in cosmological studies.

The Magellanic Clouds are among only a handful of galaxies where the magnetic field can be studied via both Faraday rotation of the polarized emission from background sources (sensitive to the line of sight field) and the polarized component of the diffuse emission (sensitive to the field direction in the plane of the sky). Studies of the Clouds at GHz frequencies (???) have been useful in determining field strengths and morphology. Low-frequency observations will contribute by locating regions, perhaps associated with wind-blown superbubbles, of warm ionized gas unseen in X-rays, and by allowing more detailed studies of Faraday structures. The MWA will investigate the existence of a possible pan-Magellanic magnetic field via the old relativistic electrons population which will have travelled far from its source.

3.5 Cosmic Ray Mapping

One of the most exciting possibilities of the MWA survey at the lowest frequencies is the mapping of the three-dimensional cosmic ray emissivity of the Milky Way. Within the MWA frequency range, HII regions turn optically thick blocking emission from the synchrotron background from the Galaxy. These HII regions will therefore appear in absorption relative to the surroundings and the residual surface brightness

at these positions allows a direct measurement of the integrated emissivity of cosmic-ray electrons out to the HII region.

Nord et al. (2006) used 74 MHz VLA observations of HII regions to detect such absorption against the Galactic synchrotron background. They found 92 regions with absorption features, 42 of which have measured distances. While such features have been seen since the 1950s, previous observations had poor resolution; but the 10 arcmin VLA beam allowed for better spatial resolution while still remaining sensitive to low surface brightness.

Because Galactic HII regions have well-constrained distance estimates, MWA measurements of the synchrotron absorption features will allow for a 3D map of the relativistic gas content in the Milky Way. Since the MWA will have a view of the inner and outer Galaxy, we can provide the first accounting of the overall distribution of Galactic cosmic rays as well as the large-scale magnetic fields that cause them to emit.

3.6 A Hidden Population of Galactic Supernova Remnants?

Statistical studies of supernova rates suggest that there should be $\sim 1000 - 2000$ supernova remnants (SNRs) in our Galaxy, in stark contrast to the ~ 300 SNRs currently known. This deficit is likely due to the observational selection effects, which discriminate against the identification both of old, faint, large SNRs, and young, small SNRs. Discovery of these ‘missing’ SNRs, and hence a characterization of the full SNR population, is crucial for understanding the production and energy density of Galactic cosmic rays and the overall energy budget of the interstellar medium.

Recent studies have demonstrated that low-frequency interferometric maps are a very efficient way of identifying new SNRs, because of the comparatively steep radio spectra of these systems. Most notable has been the survey of Brogan et al. (2006), shown in Fig.7, which tripled the number of known SNRs in a 40 deg^2 patch of the Galactic plane. The MWA will have a unique view of virtually all the inner Galaxy. The high-quality images that we expect to derive, across a range of frequencies, will provide a superb data set from which to identify hundreds of previously unidentified SNRs. These sources will be of interest both as a statistical ensemble, and because among them will be individual objects with unique or extreme properties.

3.7 Radio Recombination Lines

Low-frequency radio recombination lines (RRLs) are a sensitive tool for probing interstellar plasma. Below 100 MHz, carbon RRLs have been detected, but only in absorption, indicating an association with cold (< 50 K) neutral gas or molecular clouds. At the frequencies above 100 MHz, both carbon and hydrogen recombination lines have been observed, with the hydrogen lines likely associated with normal HII regions as at higher frequencies. Both carbon and hydrogen lines have been found in measurements along the Galactic plane as far as ± 4 deg in Galactic latitude.

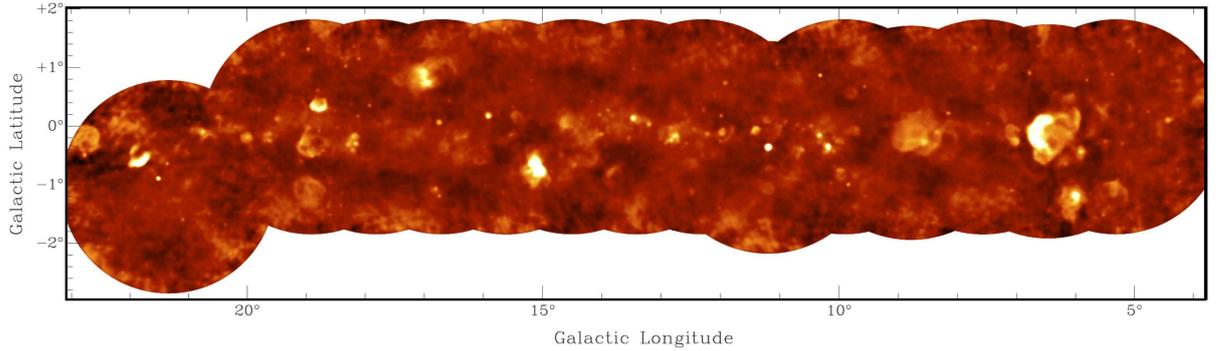


Figure 7: A 330-MHz panorama of part of the Galactic first quadrant, derived by smoothing VLA data from Brogan et al. (2006) to 3 arcmin resolution. At these low observing frequencies, most of the bright sources correspond to non-thermal emission from SNRs. The MWA will be able to carry out such observations over almost the entire inner Galaxy.

Measurements of RRLs in the MWA frequency range will provide an opportunity to study both emission and absorption processes are important, yielding estimates for both electron temperature and density, and exploring in better detail the diffuse photodissociation zones that lie between molecular clouds and the general ISM. Carbon RRLs at 75 MHz exhibit a linewidth range from 5–50 km s⁻¹ (Erickson, McConnell, Anantharamaiah 1995), corresponding to 1–12 kHz. Although, the MWA spectral resolution is not ideal for such narrow lines, single-pixel RRL observations have previously been used with much success (Alves et al. 2011). Sensitivity can also be regained by stacking different transitions within the observing band.

4 Time-domain Astrophysics

Systematic exploration of the time domain is becoming a dominant frontier in astronomy, and significant resources have been deployed across the electromagnetic spectrum in order to probe and understand transient and time-variable phenomena. Radio transients vary on time scales of seconds to days. The sources are compact objects or energetic/explosive events, and each type is being investigated at the forefront of astrophysics.

Radio observations can provide keys to understanding the explosive and transient universe by directly measuring the effects of magnetic fields and non-thermal processes that drive the outbursts (e.g., Cordes et al. 2004). Even more intriguingly, synergies with multi-messenger astronomy (correlating electromagnetic transients with events detected in gravitational waves or neutrinos) have the potential to unlock substantial new physics. The MWA spans the upper frequencies associated with coherent radio sources and the lower frequencies of non-thermal MHD processes. This makes transient observations with the MWA particularly useful for understanding the non-equilibrium processes which drive dynamic astrophysical systems.

The potential sources of radio transient emission fall into five broad categories: coronal emission from nearby stars/substellar objects, emission from compact objects such as neutron stars and accreting black holes, explosive events such as GRBs and radio supernovae, planetary emission from nearby systems, and new phenomena discovered through the opening of a new region of observational phase space. Of these, the first three are known sources of transient radio emission (at least at some frequencies), while the last two categories constitute more speculative targets. For those there are firm theoretical expectations that these objects should give rise to transient radio emission, and our searches will be far deeper than previous surveys.

First, we discuss in detail some of the expected physical constraints to be gained from the MWA observations of known sources of transients (§ 4.1). We then explore some of the more speculative science targets that we hope to explore with the new phase space opened up by the MWA (§ 4.2). Finally we describe the new capabilities afforded by the MWA (§ 4.3). We note that two related discussions are in Sections 4.4 and ?? : Section 4.4 discusses observations of pulsars which can be both steady and transient sources, while Section ?? discusses the propagation effects that limit observations of both pulsars and fast transients.

4.1 Known Transient Targets

Low-Mass Stars and Brown Dwarfs Magnetized plasmas in stellar coronae (the outer layers of a star’s magnetosphere) produce strong radio emission through non-thermal, collective, and/or coherent processes. This emission reflects local properties such as density and magnetic field strength, and can be used to understand magnetic field generation, magnetospheric structure, angular momentum evolution, magnetic flaring mechanisms and accretion processes. Furthermore, magnetic fields provide one of the few indirect probes of stellar interiors.

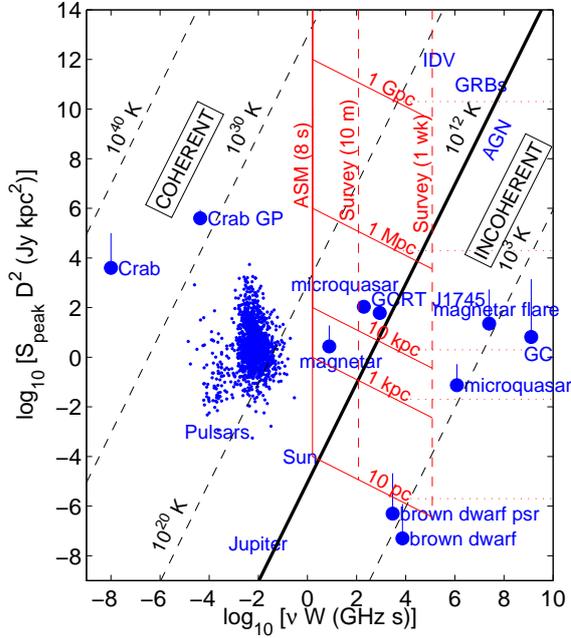


Figure 8: Phase space for radio transients observable with the MWA at a nominal frequency of 200 MHz, updated and adapted from Cordes et al. (2004). We plot the product of the observed peak flux density S_{peak} and the square of the distance D^2 (like a luminosity) against the product of the emission frequency ν and the transient duration W . In the Rayleigh-Jeans approximation, these quantities are directly proportional and related to the brightness temperature T (given by the diagonal lines); we use a brightness temperature of 10^{12} K (thick diagonal line) to divide coherent and incoherent processes (Readhead 1994). The red lines show the predicted sensitivity of the MWA, assuming a 1 Jy source can be detected in 8 s. The vertical red lines give the timescales for individual snapshot observations (8 s), and short- and long-term surveys (10 m and 1 week). The red diagonal lines give the $S_{\text{peak}} D^2$ limits corresponding to distances of 10 pc (appropriate for sources such as low-mass stars, brown dwarfs, and planets), 1 kpc (local Galactic sources), 10 kpc (the Galactic Center), 1 Mpc (local group) and 1 Gpc (extragalactic sources).

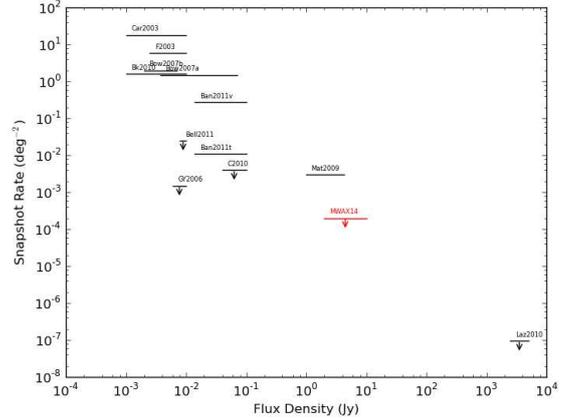


Figure 9: Tara’s figure here. We plot snapshot rate versus flux density threshold for blind surveys...

While radio studies of late-type stars and active binaries are well-established (see Güdel 2002 for a review), radio observations of the lowest mass stars and brown dwarfs — objects incapable of sustained core hydrogen fusion (Kumar 1962) — have only recently been demonstrated, and comprise a relatively new tool in this active field of research. M dwarfs with masses $0.1\text{--}0.5 M_{\odot}$ are a dominant stellar component of the Galaxy, comprising $\sim 70\%$ of all stars. They are also known to exhibit high levels of magnetic activity, with strong surface magnetic fields ($\sim 2\text{--}4$ kG, compared to ~ 10 G on the Sun; Saar & Linsky 1985; Johns-Krull & Valenti 1996) and substantial filling factors (50–80% of the surfaces of M dwarfs are covered by magnetic fields; Johns-Krull & Valenti 1996). Magnetic radio emission from M dwarfs has been observed in many nearby systems, both flaring and quiescent, predominantly in the 1–10 GHz band. These studies have confirmed the existence of large-scale, organized magnetic fields around stars with fully convective interiors (Donati et al. 2006), despite the loss of $\alpha\Omega$ dynamo that powers the Solar field (Parker 1955).

For even lower mass stars and brown dwarfs, the detection of both quiescent and flaring radio emission was initially a surprise (Berger et al. 2001), as the flux from these sources is orders of magnitude greater than that expected from the Güdel-Benz relation³. Several late-type sources have now been detected at GHz frequencies (Fig. 8), in many cases despite the absence of optical or X-ray emission (see Berger 2006 for a review). Indeed, while $H\alpha$ and X-ray luminosities relative to bolometric luminosities appear to decline with spectral type, relative radio emission inexorably increases up to the substellar regime (see Burgasser & Putman 2005; Berger 2006; Audard et al. 2007). Understanding why radio emission is so prominent among these very low mass objects, and whether such emission correlates with age, rotation or other physical pa-

³A correlation between radio flux and X-ray luminosity that extends over several orders of magnitude; see Güdel & Benz 1993.

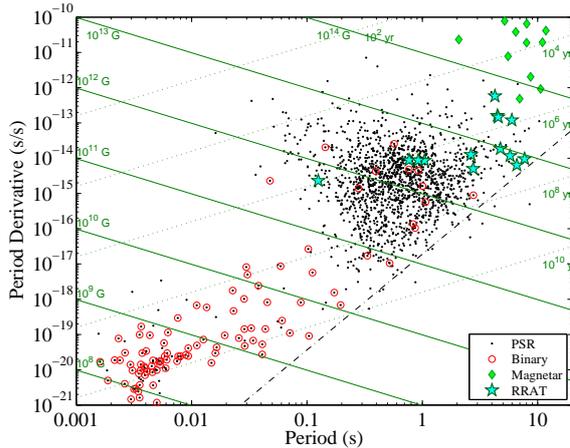


Figure 10: P - \dot{P} diagram showing the distribution of the known pulsar population. The diamonds show the magnetars (SGRs and AXPs) and the stars the RRATs; binary systems are circled. The diagonal lines show loci of constant dipole magnetic field (solid) and spin-down age (dotted), while the dot-dashed line is an approximate “death-line” for pulsar activity. The MWA will be uniquely sensitive to the slower, transient population while maintaining sensitivity to a considerable fraction of the millisecond pulsar population in the lower left.

rameters, remain outstanding questions.

Radio flares in particular demonstrate that this emission is associated with magnetic events, occurring over timescales of microseconds to minutes (e.g., Osten & Bastian 2006). The brightness temperatures of bursting emissions frequently exceed 10^9 K, indicating coherent processes as confirmed by high circular polarizations (30–100%). Yet radio variability from these sources is remarkably diverse, from strong (30 mJy peak flux), narrowband, fully polarized, bursting emission with frequency drifts (Burgasser & Putman 2005); to periodic bursts suggestive of pulsar-like beaming (Hallinan et al. 2007, and Fig. 8); to order-of-magnitude variations spanning years (Antonova et al. 2007). It has even been suggested that the observed “quiescent” emission from these sources may be the result of low-level, sustained electron cyclotron maser emission (e.g., Hallinan et al. 2007). The physical origin of transient radio bursts from low-mass stars, their incidence rates (duty cycle estimates range from 1–30%) and their spectral characteristics are either poorly constrained or entirely unknown. These questions has a direct impact on whether low mass stars comprise a significant fraction of radio transients in general (e.g., Kulkarni & Phinney 2005; Kaplan et al. 2008).

The MWA has the potential to contribute substantially to our understanding of both quiescent and flaring magnetic emission from low mass stars and brown dwarfs. By sampling the 80–300 MHz band, the MWA observations can be used to constrain the peak frequency (ν_{pk}) and spectral indices about ν_{pk} , enabling

determination of coronal field strengths (currently estimated at 10–100 G; Burgasser & Putman 2005; Berger 2006), electron densities and the fundamental nature of the emission. Audard et al. (2007) argue that radio emission from very low mass stars may in fact peak in the ~ 100 MHz range if it arises from electron cyclotron emission from weak fields ($\nu_{\text{pk}} = \nu_c = 30$ –300 MHz for 10–100 G fields; see also Osten et al. 2006). The sensitivity of the MWA is essential for this work, given the intrinsic faintness, but variable nature, of radio emission from low-mass stars; estimates range over $10 \mu\text{Jy}$ to 100 mJy at 100 MHz at a distance of 10 pc, depending on the emission mechanism. Similarly, the MWA’s wide-field capabilities are necessary to build up statistically robust samples, particularly given the roughly uniform distribution of nearby low-mass stars in the vicinity of the Sun. High spectral resolution observations enabled by the MWA will permit studies of field dynamics and remote determinations of physical parameters such as the heights of magnetic reconnection regions, electron speeds, and the density profile of the stellar coronae.

Magnetars While a variety of neutron stars can produce transient or steady radio emission (discussed in more detail in Section 4.4, some subclasses of neutron stars can give rise to extremely energetic, explosive phenomena. With magnetic fields of $\sim 10^{15}$ G, magnetars (Duncan & Thompson 1992; Thompson & Duncan 1995) undergo catastrophic reconnection events known as “giant flares” that release $> 10^{43}$ erg. With each flare the magnetars release blobs of relativistic plasma (Frail et al. 1999; Gaensler et al. 2005; Cameron et al. 2005) with peak fluxes of hundreds of mJy at frequencies from 200 MHz up to 100 GHz (Fig. 8). Such events are detected through high-energy satellites, but the radio monitoring provides vital diagnostics of the flare properties and energetics.

Beyond this, some magnetars unexpectedly have steady radio emission that is modulated at the X-ray pulse period (2–12 s). Prior searches for steady-state radio emission from magnetars had not been successful (e.g., Kaplan et al. 2002), but Halpern et al. (2005) found a radio source coincident with the magnetar XTE J1810–197 (also Camilo et al. 2006, and others). Monitoring the magnetars through both individual pulses and phase-averaged emission, looking for both giant flares and the onset of bright phases, will help understand the duty cycles of the radio-bright phases and hence unravel the puzzles that they present.

X-ray Binaries Relativistic outflows or jets are a widespread yet transient consequence of accretion onto compact objects. Radio jets are seen for black-hole binaries (BHBs) and some neutron-star binaries (NSBs). These sources are collectively called “microquasars” (Fig. 8), since they exhibit scaled-down and rapidly evolving versions of the jets in active galactic nuclei. Microquasars exhibit several types of jets with different ranges of radio power and ejection timescale. Their study is crucially dependent on the correlated variations in radio and X-ray properties.

The most common type of jet in microquasars is the quasi-steady jet associated with the X-ray hard state (Fender et al. 2004; McClintock & Remillard 2006) that can persist for months in some sources. The steady jet is estimated to be mildly relativistic (i.e. $\sim 0.7c$; see Fender 2006), but there is uncertainty about the baryonic content and hence the scale of the mass outflow and the fraction of accretion energy needed to power the jet.

Impulsive ejections are also produced by BHBs and some NSBs and the brightest of these are seen as bipolar radio jets that are moving with velocities as high as $0.98c$ (Mirabel & Rodríguez 1999). Impulsive jets are associated with X-ray state transitions (Fender et al. 2004). In two BHBs a superluminal radio ejection, coinciding with a major X-ray flare, led to the appearance of an X-ray jet (more than one year later), that was imaged with *Chandra* as the jet impacted the local ISM (Tomsick et al. 2003; Corbel et al. 2005). Smaller and more frequent ejections in BHBs are seen as correlated X-ray and radio flares with ~ 10 min timescales and radio-band delays (Eikenberry et al. 2000; Wilms et al. 2007). The available X-ray data usually reveal recurrent and abrupt changes in flux and spectral components that associate the small jets with instability cycles in the inner accretion disk.

Study of the connection between disks and jets is fundamentally based on correlated X-ray and radio behavior, as outlined above. During the last decade, the primary limitation for this enterprise has been the absence of dedicated radio instruments that can partner with X-ray facilities, but the MWA will radically change this landscape. Additional partners for jet investigations arise with *Fermi* (10 keV to 300 GeV), and the recent expansions of TeV Observatories (e.g., HESS and VERITAS; 50 GeV to 50 TeV).

Recent measurements with the GMRT (150–1450 MHz) in India have shown variable radio emission in GRS 1915+105 (Ishwara-Chandra et al. 2005, see Fig. 8) and Sco X-1 (Pandey et al. 2005), with spectra that does not exhibit self-absorption cutoff at low frequencies. This is interpreted as emission from the outer regions of a compact jet and from an optically-thin impulsive jet, respectively (also see Pandey et al. 2006, 2007).

Overall, the MWA has the capability to monitor many known sources when X-ray activity is detected, establishing outburst statistics and extending the spectra down to low frequencies where the total energetics are constrained. These observations can help to measure the burst luminosity function and the X-ray/radio correlation, and investigate their dependences on various intrinsic source parameters such as mass and X-ray luminosity. The MWA will provide data archives for the two microquasars that are reliable sources of jets: SS 433 and GRS 1915+105, as well as the BHBs and NSBs with fastest outburst recurrence time (1–2 years: 4U 1630–47, and GX339–4, Aql X-1, 4U 1608–52, and the rapid burster). These monitoring observations will also find new outbursts of known sources, acting as a trigger for observations across the spectrum. Finally, the MWA has the potential to discover new sources: the large majority of the known BHBs and candidates

are transient sources that were discovered because of their X-ray outbursts (Remillard & McClintock 2006).

4.2 Serendipitous Transient Sources

Beyond the source categories discussed above, there are a number of object classes which we might hope to see (see Cordes et al. 2004 and Fender et al. 2006). These vary from the local to the cosmological, and the population predictions also span a wide range. Currently, low-frequency transient radio emission has been proposed but not observed for these objects, and there are only limited observational constraints. Such sources are among the most exciting possibilities for the MWA transient surveys (§ 4.3). Those surveys cover a large area of unexplored phase space — orders of magnitude in several different parameters — and provide a real opportunity to discover unique sources.

Extra-Solar Planets In the Solar System, Jupiter is a strong source of low-frequency radio emission produced by cyclotron maser processes in its magnetosphere (Gurnett 1974; Wu & Lee 1979). Observations have established that many of the Jovian planets being discovered around other stars (e.g., Marcy et al. 2005) are magnetic (Shkolnik et al. 2003), although the exact levels are not known. By analogy, many of those planets should have similar emission. This would then be a novel way of *directly* detecting the planetary companions, something that has only been possible in a few special cases otherwise (Charbonneau et al. 2002). This would allow an unprecedented probe of the planetary systems, such as estimating properties of the planetary magnetosphere, measuring its rotation rate, and observing the interaction between the star and planet (Lazio et al. 2004). Grießmeier et al. (2007) discuss theoretical expectations for radio emission from known extrasolar planets. Most of the sources are predicted to emit at the microJansky level between 10–200 MHz. A handful of planets are expected to emit at the mJy level in the MWA bandpass. Their results are heavily model-dependent and MWA observations of the currently known exoplanet population will help constrain further models.

There have been a number of searches for emission from such planets (e.g., Farrell et al. 1999; Bastian et al. 2000; Zarka et al. 2001; Lazio et al. 2004; Lazio & Farrell 2007). There are no detections to date, although the results are not very constraining. The emission is predicted to be very sporadic and bursty, and it is difficult to search effectively for such emission with pointed instruments like the VLA. Instead, new instruments like the MWA are likely to be the best way to detect extra-solar planets (Lazio et al. 2004).

Explosive Events Gamma Ray Bursts and radio supernovae may both produce short and long duration transient radio signals. The afterglow emission from each type will provide signals at the upper frequencies of the MWA that are delayed from the initial explosion (both due to effects in § ?? and to changing opacities) and slowly brighten over a few weeks to months (Morales et al. 2005). These afterglows can be

important diagnostics for explosion energetics (Soderberg et al. 2007, 2010) and can help understand particle acceleration in the nearby Universe (Chakraborti et al. 2010). While the long timescales at low frequencies make the MWA unfavorable for discovery of such events, the rarity of the more extreme ones mean that the very large FOV may compensate

GRBs, supernovae, and other explosions may also produce prompt pulses of coherent emission during the initial explosion (Colgate & Noerdlinger 1971; Nakar & Piran 2011). The theorized prompt signals are produced by coherent emission near the explosive shock. Proposed mechanisms include current oscillations (Usov & Katz 2000), synchrotron maser activity behind the shock (Sagiv & Waxman 2002), or collective plasma modes as seen in solar bursts (Moortgat & Kuijpers 2005). Models by Hansen & Lyutikov (2001) and Benz & Paesold (1998) also predict detectable emission, depending on the plasma environment and dynamics of the GRB. Some of these signals will be accompanied by bursts of radiation at other wavelengths, while some may offer the potential for multi-messenger astronomy by correlating radio and gravitational-wave signals (Nakar & Piran 2011; Palenzuela et al. 2010).

Detection of such prompt emission from GRBs offers a number of unique insights into the properties of the bursts, the intergalactic medium, and cosmology (Morales et al. 2005). First, the details of the emission that we see depend heavily on the specific model for the shock structure, as discussed above. Second, we can use the emission as a probe of the media through which it propagates: we will see delays and dispersion from the local plasma, the host galaxy’s ISM, the intergalactic medium (details of which can depend on cosmic reionization), and the Milky Way’s ISM (Inoue 2004).

Past searches for prompt radio emission from GRBs (Dessenne et al. 1996; Benz & Paesold 1998; Balsano 1999) were all unsuccessful. Other projects attempted to perform blind surveys for radio transients (Amy et al. 1989; Baird et al. 1976; Katz et al. 2003). All of these attempts have suffered from constraints inherent in narrowband receivers and simple transient identification systems. More modern projects like GASE and ETA (Morales et al. 2005; Patterson et al. 2008) were designed to correct many of these problems, with digital baseband recording and interference rejection through de-dispersion, but the collecting areas are still very small.

Unknown Opportunities Above we discussed two classes of sources that are expected to emit low-frequency radio transients, and where detection of such transients would enable us to make significant advances in our understanding of such objects, but where we do not know the source properties enough to consider them “guaranteed” science. Beyond even those classes are additional objects that may be found with blind searches (e.g., neutron star binary inspiral events that may produce radio precursors; Hansen & Lyutikov 2001).

To date, systematic transient searches with radio telescopes have yielded some results, but they have largely been difficult to interpret (e.g., Matsumura et al.

2007, 2009), due to poor statistics, limited localization, and a long time before follow-up. However, there have been successes that, while enigmatic, hint at the potential offered by the MWA. We do not give a full review here, but point to particular detections that hold promise for the MWA.

While searching for transient events at the Galactic Center (GC), Hyman et al. (2002) found two sources, one of which is an X-ray binary, but the other remains unclassified, although it varies on long timescales (\sim months). Later searches (Hyman et al. 2005, also see Hyman et al. 2008) found a much more rapidly variable source, with flares on timescales of minutes that repeated (sometimes) every 77 min (GCRT J1745 in Fig. 8). The positional coincidence with the GC, along with the greatly increasing source density near the Center, suggests it is at a distance of about 8 kpc, but this could be a selection effect because all the fields searched for transients in the program were in that direction. Bower et al. (2005) found another transient near the GC, but they deduced that it was an X-ray binary with a jet outburst (see § 4.1) interacting with the dense medium in that region. Finally, Bower et al. (2007) searched archival VLA data and identified very faint (sub-mJy) transient sources. Based on position coincidence with known galaxies, some were probably supernovae, but others still have no known classification (also see Becker et al. 2010; Bower & Saul 2011; Bannister et al. 2011). Only recently have surveys moved beyond serendipitous examinations of archival data (e.g., Bannister et al. 2011), with a wide range of flux limits and timescales, to systematic examinations of the variable sky (e.g., Lenc et al. 2008; Croft et al. 2011). It is becoming clear that radio transients, are rare but promising targets that will lead to advances in a number of areas of astrophysics.

4.3 Planned Searches & Limitations

We will conduct a continuous search for transient radio emission in each image produced by the MWA’s real-time system, looking for changes from the previously observed sky on timescales ranging from seconds to months (eventually using the high-quality integrated data from the sky surveys). This search will be more than six orders of magnitude more sensitive than previous transient surveys in the band and will cover a much broader range of frequencies, transient durations, and dispersion delay.

Eventually the full transient capabilities of the MWA will: (1) cover $\sim 1/4$ ster instantaneously ($\sim 3\%$ of the visible sky) with full polarization coverage; (2) search blindly over that area orders of magnitude deeper than previous work; (3) simultaneously record light curves and spectra for hundreds of sources, routine observation of 10s of thousands of sources per week; (4) obtain typical exposures of days/source, with hundreds-to-thousands of hours for sources in selected areas (galactic plane, EOR fields) over one year; and (5) record full electric field time-series for a subset of observations. t

New sources will have relatively poor localization. This will hinder interpretation as many possible counterparts will be present at other wavelengths (e.g., Ka-

plan et al. 2008). Prompt multi-wavelength follow-up with wide-field imaging instruments will be crucial to help mitigate this, as detection of contemporaneous variability at other wavelengths will significantly improve the localization of sources and pave the way for more detailed follow-up observations such as spectroscopy.

Source confusion will limit the sensitivity of the MWA for source detection. However, time variability is a classic way to help beat the confusion limit (i.e., searches for pulsars with single-dish telescopes). Subtracting images of the sky taken over successive time periods will help beat down the confusion noise and allow transients to emerge, especially when correlated with observations at other wavelengths. Finally, examining of polarized images that have much lower background source levels will allow searches for bright and highly polarized transients like GCRT J1745–3009 (Hyman et al. 2005).

4.4 Pulsars

With almost 2000 now known (Fig. 10), pulsars offer opportunities to study a range of astrophysical phenomena, from the microscopic to the Galactic. The potentially wide coverage in frequency, combined with its collecting area, makes the MWA a unique instrument for low frequency detection and detailed studies of pulsars and transients. The areas of pulsar science that the MWA would open up at low-frequencies include pulsar phenomenology and pulsar searches, in general, and single-pulse and giant pulse studies, in particular.

The MWA will be able to observe at rates faster than the 0.5–8 s correlator integrations using a voltage capture system capable of recording, for several hours, correlator input data. This system will provide 3072×10 kHz Nyquist sampled channels of undetected voltages from each of the 128 antennas of the the MWA that will enable high time-resolution studies of several types of objects, including pulsars and fast transients.

It is at MWA frequencies that pulsar emission peaks (Maron et al. 2000) and that interstellar propagation effects are easiest to study, but it has been neglected for years because of difficulties in processing the data and the increasing prevalence of radio frequency interference (RFI). This has left the low-frequency pulsar population largely unconstrained. Since low frequencies select against distant objects (especially for fast pulsars) the MWA will provide unique constraints for the local, low-frequency population. As a baseline, in an 8 hour pointing at 200 MHz we should have a 8σ sensitivity limit of 1.8 mJy for long-period pulsars. When corrected to 1400 MHz using a spectral index of -1.8 (Maron et al. 2000), this would be 0.05 mJy, comparable to or better than ongoing surveys like the High Time Resolution Universe survey (Keith et al. 2010) or the Green Bank 350 MHz Driftscan Survey (Boyles et al. 2012, in prep. and Lynch et al. 2012, in prep.).

Studies of individual pulsars help address a number of areas of astrophysics. Studies of the individual pulses provide unique insight into the as-yet poorly understood pulsar emission mechanism and astrophysical

plasmas (Melrose 2003). Assembling an average pulse profile from thousands of individual pulsars can help investigate the emission further, probing the emission altitude, beam geometry, the inclination of the magnetic field from the spin axis (Jenet et al. 2001; Gupta & Gangadhara 2003), and statistics derived from this may be among the best probes of complicated phenomena like core-collapse supernova (e.g., Johnston et al. 2005). Longer timescale variations in the emission can directly constrain the density of the magnetospheric plasma (Kramer et al. 2006).

Single-pulse studies should be possible⁴ for a sample of pulsars in excess of 100, with the full MWA system at frequencies > 100 MHz. In cases of bright pulsars, we aim to probe the polar emission regions at different heights in greater details to study single-pulse fluctuations simultaneously across a wide range of radio frequencies, believed to come from different heights from the star surface. Mapping of the emission patterns corresponding to different heights simultaneously will enable tomography of the pulsar emission cone (Asgekar & Deshpande 2001; Deshpande & Rankin 1999). The wide bandwidth of MWA would probe a large fraction of the emission cone at farther heights from the star, revealing much needed clues about the mechanism of pulsar radio emission, which is still very poorly understood even after 40 years of pulsar studies.

4.4.1 Rotating Radio Transients

While observations of steady pulsar emission reveal much about those sources, it is in sources where the steady pulsar emission fails that we can hope to gain disproportionate insight about the pulsar emission mechanism and the relation of pulsars to other more exotic classes of neutron stars. In particular, the Rotating Radio Transients (RRATs; McLaughlin et al. 2006 and Figure 10) likely serve as links to other more extreme populations. The RRATs emit only sporadic dispersed radio bursts of between 2 and 30 ms in duration that are separated by 4 min to 3 hr, but nonetheless are identifiable as rotating neutron stars by their long-term spin-down. Initial estimates suggest that there could be as many RRATs as traditional pulsars (McLaughlin et al. 2006; Keane et al. 2010), but their properties do not appear the same, as they occupy different parts of the $P - \dot{P}$ diagram.

The study of RRATs and sources with and without radio emission may help link the canonical rotation-powered pulsars—neutron stars that emit primarily in the radio and that are powered by rotational energy—to other classes of neutron stars that are powered via other energy sources. In particular, the X-ray and γ -ray sources known as magnetars (Woods & Thompson 2006), which manifest observationally as the roughly 9

⁴The fractional magnitude of pulse-to-pulse variation in the conal profiles is expected to be close to unity. Therefore, although desirable, it is not crucial to have the ability to detect individual pulses from the sequences for assessing primary parameters of these fluctuations, since the detection of relatively stable fluctuation features/properties benefits from the total integration time in quite the same way as the average profile estimation does.

known Anomalous X-ray Pulsars (AXPs) and 7 Soft-Gamma-Ray Repeaters (SGRs), are powered by decay of superstrong ($\gtrsim 10^{14}$ G) magnetic fields. In contrast, the soft X-ray sources known as Isolated Neutron Stars (INS; Kaplan 2008) are powered by residual heat, but may be the decayed remnants of old magnetars (Kaplan & van Kerkwijk 2009). There is currently a great deal of interest in linking radio pulsars to these populations. At least two magnetars have been seen as transient radio pulsars (Camilo et al. 2006, 2007), while radio searches for the INS have so far been negative (Johnston 2003; Kaplan et al. 2003; Kondratiev et al. 2009). The populations may be linked via RRATs: the X-ray and timing characteristics of the RRATs offer tantalizing clues to their relation to both magnetars (Lyne et al. 2009) and the INS (Popov et al. 2006; McLaughlin et al. 2007), but as yet nothing firm has been established (Keane & Kramer 2008).

Identification of RRATs relies on detecting single, dispersed pulses rather than steady sources (as in Burke-Spolaor & Bailes 2010); they do appear as repeating transients, and so many of the techniques required will be similar to those for other transients, although for the fastest timescales the instrumental capabilities discussed below will be important.

4.4.2 Interstellar Medium

Beyond the study of pulsars themselves, variations in the individual pulses with time and frequency can be used to probe the properties of the interstellar medium (ISM) via dispersion (Cordes & Lazio 2002), scintillation (Rickett 1969), and scattering (Bhat et al. 2004). These propagation effects can then be used to study the Galactic magnetic field (Noutsos et al. 2008), the solar corona (Ord et al. 2007). Signals of short intrinsic duration do not survive passage through interstellar/intergalactic plasma unscathed. Two effects smear out the signals, dispersion and scattering (see, e.g., Rickett 1990; Cordes et al. 1991; Taylor & Cordes 1993).

Dispersion makes lower frequencies arrive later. Compared to a signal at infinite frequency, a signal of frequency ν arrives at a time delay $\propto \nu^{-2}$. Dispersive delay can be both an advantage and a disadvantage. Searching for a radio counterpart to a transient event observed with a high-energy satellite (or even with non-electromagnetic facilities like gravitational wave interferometers) such as a gamma-ray burst, we would have as much as several minutes to hours to prepare for the event at low frequencies (e.g., Cordes & McLaughlin 2003; Macquart 2007). But the converse is also true: by the time we detect a transient signal, it may be too late for other facilities to observe it.

Scattering is the result of multi-path propagation in ionized media. While it has other effects, such as spectral and angular broadening, we are primarily concerned with temporal broadening here. This leads to information on timescale shorter than the scattering time being lost, and this time scales as $\propto \nu^{-22/5}$. Because of this steep scaling this tends to set a minimum useful timescale for low-frequency observations. The scattering timescale becomes comparable to the stan-

dard MWA correlate integration time in the Galactic plane for objects beyond ~ 5 kpc (Cordes & Lazio 2002).

5 Solar, Heliospheric, and Ionospheric Science

The MWA will make significant contributions to the fields of solar, heliospheric, and ionospheric (SHI) science through a diverse set of novel radio measurements, as described here and in earlier papers (Bastian 2004; Cairns 2004; Oberoi & Kasper 2004; Salah et al. 2005; Oberoi & Benkevitch 2010). These measurements directly address space weather, defined as the study of the impact of the Sun on the Earth and its neighborhood. Space weather effects are mostly driven by solar flares and coronal mass ejections (CMEs) that produce electromagnetic radiation (from X-rays to radio wavelengths), energetic particles, shock waves, changes in magnetic fields, and fast-moving plasma outflows that couple to the magnetosphere, ionosphere, neutral atmosphere, and surface of the Earth. These responses can directly affect humanity's environment, technology, and society (Scherer, K., Fichtner, H., Heber, B., & Mall, U. 2005; Warmuth & Mann 2004). The measurement, modelling, and prediction of space weather are major foci of international space research. The ability of the MWA to observe and track CMEs, shocks, and other plasma structures from points close to their inception, along with characterization of their magnetic field and their eventual impact on the terrestrial ionosphere, will make it a powerful instrument for space weather studies.

The remainder of this section is divided into subsections for solar, heliospheric, and ionospheric objectives.

5.1 Solar Science

Even the quiet radio Sun is a time variable, spectrally and morphologically complex, extended source. The temporal, spectral and morphological dynamics of emission features is especially remarkable during periods of high solar activity. The active Sun produces both broadband ($\Delta f/f \approx 1$) and narrowband ($\Delta f/f \ll 10^{-2}$) emissions with frequencies from about 30 GHz to below 1 MHz (e.g., Wild et al. 1963; Bastian et al. 1998; Cane et al. 2002; Karlický 2003; Cairns 2011). Solar radio emission shows variations at time scales ranging from less than a millisecond to the eleven-year cycle of solar activity and a rich structure in frequency, presenting a challenging radio imaging problem. The unprecedented instantaneous dynamic range, good spectral sampling of the 80-300 MHz band with a high spectral resolution (40 kHz), and precision full-Stokes calibration of MWA will enable spectroscopic imaging of the dynamic Sun.

Solar radio emission in the MWA frequency range falls into three distinct categories. Thermal emission is produced by hot electrons in all layers of the solar atmosphere, but especially the solar corona, as reviewed

by McLean, D. J. & Labrum, N. R. (1985). Gyrosynchrotron and synchrotron emission with broad power-law spectra in frequency are created by electrons accelerated in magnetic loops, in one interpretation for type IV bursts (McLean, D. J. & Labrum, N. R. 1985; Bastian et al. 1998), and by shocks driven by coronal mass ejections (Bastian et al. 2001). Intense bursts of (nearly coherent) narrow-band emissions, whose central frequency can vary across the MWA frequency range, are produced as the so-called type I to V bursts (e.g., Wild et al. 1963; McLean, D. J. & Labrum, N. R. 1985; Cane et al. 2002; Cairns 2011). The presence of multiple different emission mechanisms, along with propagation effects like refraction and scattering, endow radio observations with a rich and unique coronal diagnostics capability. This is illustrated by the fact that counterparts of solar type I through V bursts at other wavelengths have not yet been established, even though they represent significant coronal dynamics and tend to be rather bright at low radio frequencies.

The large gradients in electron density and temperature from the chromospheric to the coronal regions lead to an even larger gradient, about seven orders of magnitude, in the value of the absorption coefficient, κ , in this region. These large gradient has the consequence that the optical depth, τ , tends to be a sensitive function of the ray path, which itself is determined by the refraction due to the large scale density gradients. This suggests the possibility that a set of solar brightness temperature (T_B) images at different frequencies can be used to independently determine both the coronal electron density, n_e and temperature, T_e , distribution in the lower corona. As the τ of ray paths at different frequencies is dominated by contributions from different coronal heights, a set of T_B images across the 80-300 MHz MWA band will make it possible to construct a 3D distribution of electron density and temperature in the lower corona for the quiescent Sun.

Solar radio bursts are one of the primary remote signatures of electron acceleration in the corona and inner heliosphere and we focus on type II and type III radio bursts. A wealth of information about them has been amassed, primarily from studies of their emission in frequency-time dynamic spectra. Their imaging studies remain rare.

In dynamic spectra, type II bursts often appear as a pair of drifting emission bands, whose frequencies differ by a factor close to 2.0 (within about 20%), taking of order 5 minutes to pass through the MWA frequency range, moving from high to low frequencies. Their flux densities typically lie in the range 10^3 – 10^5 SFU (10^{-19} – 10^{-17} Wm $^{-2}$ Hz $^{-1}$) (Nelson & Melrose 1985; Suzuki & Dulk 1985; Cairns 2011). Type III bursts have a similar frequency-time structure but drift about a factor 300 faster and so might spend only 1–3 s in the MWA band. Type IIs are typically weaker than type IIIs in strength, from about 10^4 SFU down to instrument sensitivity limits and differ in their polarization properties (Nelson & Melrose 1985; Suzuki & Dulk 1985; Cairns 2011).

The detailed polarization properties of type II and III bursts will be an area of significant research for

MWA. Major unresolved theoretical issues exist due to the relatively small observed levels of circular polarization observed, despite existing theories predicting essentially 100% circular polarization in the sense of the o mode (lefthand) (Nelson & Melrose 1985; Suzuki & Dulk 1985; Cairns 2011). The MWA's fully electronic data with very good frequency and temporal resolution should establish the observational properties and allow significant theoretical progress to be made.

Type IIs are interpreted in terms of a shock moving at speeds of 400–2000 km s $^{-1}$, whereas type IIIs are due to bursts of electrons moving at speeds of order one third of the speed of light, produced in magnetic reconnection sites during solar flares (Wild et al. 1963; Melrose 1980; Bastian et al. 1998; Robinson & Cairns 2000). Type IV bursts are correlated with type II bursts, often being interpreted as continuum emission behind the shock, while type V bursts are often believed to be composed of multiple unresolved type III bursts.

The standard models for these bursts involve generation of radiation near the electron plasma frequency, f_{pe} .

$$f_{pe} \approx 9n_e^{1/2} \text{ MHz}, \quad (4)$$

where n_e is in m $^{-3}$, and near $2f_p$. This “plasma emission” mechanism involves generation of electrostatic Langmuir waves near f_p by electron beams and the conversion of these Langmuir waves into radio emission via various linear and nonlinear conversion processes (Ginzburg & Zhelezniakov 1958; Melrose 1980; Robinson & Cairns 2000; Cairns 2011). Since n_e decreases with increasing distance from the Sun, the emission frequency is expected to decrease with time as the source moves away from the Sun. For type II, III, and V bursts at MWA frequencies these beams of energetic electrons typically move away from the Sun; they are believed to result from electron acceleration in magnetic reconnection regions (types III and V) and at MHD shocks (type IIs).

Type II bursts are associated with suprathermal electrons ($E > 100$ eV) accelerated at shocks (Wild et al. 1963; Melrose 1980; Nelson & Melrose 1985; Bastian et al. 1998; Cairns 2011). At present a major unresolved question is whether type II bursts in the corona are associated with a blast wave (i.e., a freely propagating shock) or the bow wave found upstream of a CME that is expanding into the heliosphere Cane & Erickson (2005); Vršnak & Cliver (2008); Cairns (2011). However, it is well accepted that type II bursts produced in the solar wind, say beyond about $4R_S$, are associated with CME-driven shocks Cane & Erickson (2005); Vršnak & Cliver (2008); Cairns (2011). The rapid spectroscopic imaging capability of MWA is expected play an important role in answering this question by providing radio images to compare against CME observations from STEREO, HINODE, Solar Dynamics Observatory (SDO) and Wind spacecraft.

The interpretation of type II and III bursts in terms of shocks and fast electron beams, respectively, relied on using a model for coronal electron density $n_e(r)$ and the fact that $f = f_p$, or $f = 2f_p$, where f is the frequency of emission to convert observation of f into a measurement of radial distance, r , from the cen-

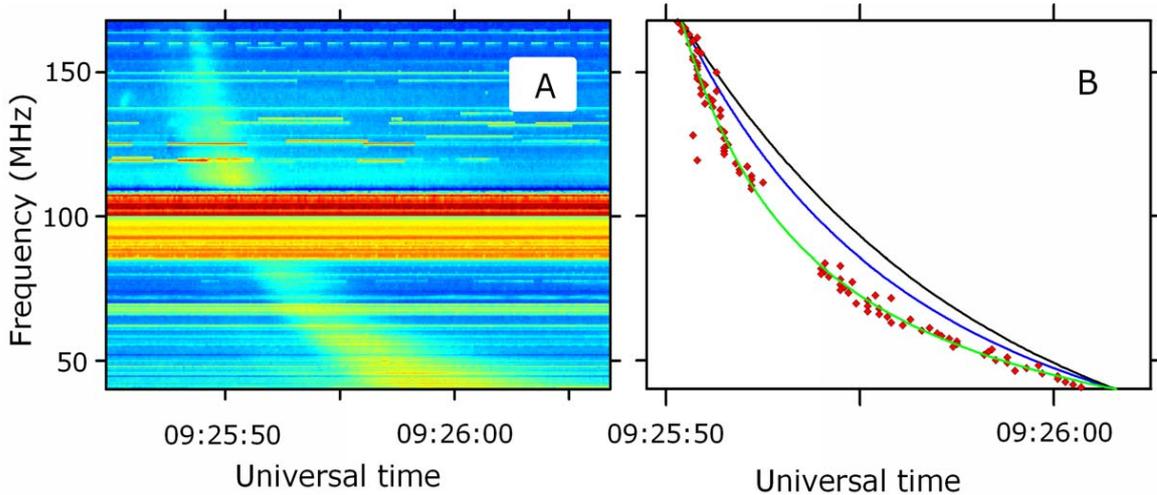


Figure 11: (a) Dynamic spectrum of the type III burst of 0926 UT on 26 October 1999, with normalized intensity color coded as a function of frequency f and time t (Cairns et al. 2009). (b) Red diamonds show the (f, t) locations of flux maxima for each t . The green line is the best fit to $f(t) = a(t - b)^{-\beta/2}$ and implies that $n_e(r) = n_0(r - 1.0R_S)^{-\beta}$ with $\beta = 2.0 \pm 0.3$. This unexpected result is a solar wind-like profile for $n_e(r)$. Fits for the leading power-law term $\beta = 6$ of the standard density model based on coronagraph data (blue line) and an exponential gravitational-settling profile (black line) agree poorly with the type III data.

ter of the Sun (e.g., Wild et al. (1963)). This approach can be inverted to find $n_e(r)$ from the time-varying frequency $f(t)$. Indeed, the power-law index of the density profile $n_e(r)$ can be obtained from $f(t)$ with the sole assumption being a constant shock speed Cairns et al. (2009); Lobzin et al. (2010), as illustrated in 11. The resulting indices to date are much lower than expected on the basis of previous models, but the $n_e(r)$ profiles appear semi-quantitatively consistent, with interesting implications for the formation of the corona. This will be an exciting area for study with MWA data.

Detailed models for the source regions and dynamics spectra of type II burst emission have recently become available, as reviewed in Cairns (2011). New MWA images and dynamic spectra of type II emission for specific solar events, in conjunction with independent coronagraph images of CMEs and other moving density structures and comparisons with the theoretical predictions, are therefore expected to lead to determine definitively the relationship between type II bursts, CMEs, and shocks and to provide strong tests of theory and our understanding of the propagation of radiation between the source and Earth. This improved understanding of type II bursts and CMEs will be vital for confidently tracking CMEs from the Sun to Earth through the corona and solar wind, characterizing their magnetic field configuration using Faraday rotation studies (Section 5.2.1), and predicting their space weather impacts.

The MWA should make fundamental contributions to our understanding of the acceleration mechanisms, generation processes, and time-varying locations and properties of emitting regions, as well as the propagation of radiation from the source to the Earth through

the time-varying and spatially inhomogeneous corona and solar wind.

5.2 Heliospheric

5.2.1 Faraday Rotation

With an increasing reliance on the robust functioning of satellites, mankind is now more affected by space weather than ever before. Reliable predictions of space weather are needed to protect our technological assets in orbit as well as humans in space. The largest of the space weather events are caused by CMEs, and the geo-effectiveness of CMEs is closely tied to the presence of a southward directed magnetic field in the CME. Currently the only operational means of obtaining this information is from the *in-situ* observations by the near-Earth satellites. This approach suffers from two significant disadvantages: 1) These measurements provide a lead time of only a few hours, consequently the advance warning comes so close to the event itself that it leaves little opportunity to take any remedial measures. 2) At these crucial times, when the satellites are swimming in CME plasma, their own performance is degraded and the communication bandwidths get reduced.

Faraday rotation (FR) observations of background polarized radio sources is the only known remote sensing technique sensitive to the orientation and magnitude of the magnetic field. FR is a dispersive property of magnetized plasmas that results in the rotation of linearly polarized radio waves. Emission at wavelength λ rotates by an angle $\phi = \lambda^2 RM$, where the Rotation Measure (RM) is proportional to the integral of the

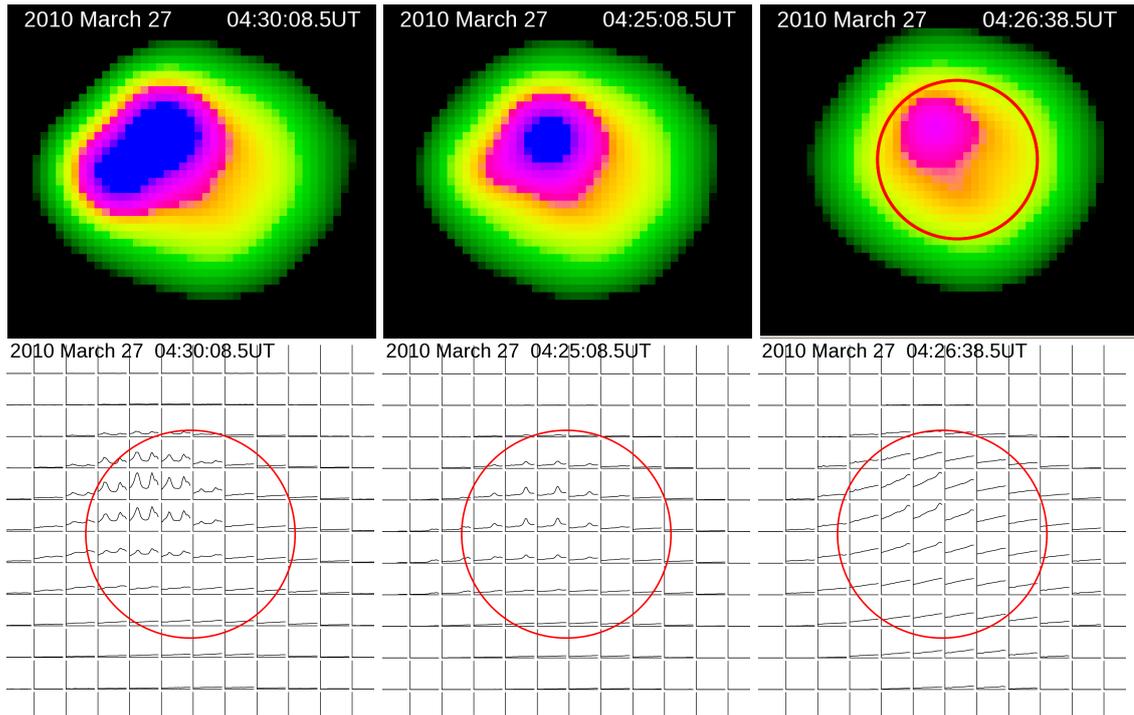


Figure 12: The top panels show a set of radio images 193.3 MHz (XX polarization) on the same intensity scale (0-2500, arbitrary units). From left to right, the first one comes from a time close to the peak of a weak non-thermal emission feature lasting ~ 10 s and occupying the entire ~ 30 MHz of observing bandwidth, the second is during one of the numerous weaker events which spanned ~ 5 s and ~ 5 MHz and last one shows an image of the quiescent Sun. The dynamic range of these images is ~ 2500 and exceeds that of earlier images by about an order of magnitude. The bottom panels show spatially localized spectra of emission across the solar disc at the same times as the top panels. The spectra are shown for every third pixel, the pixel size is $100'' \times 100''$. The spectra span the entire observing bandwidth, binned into 24 frequency bands spaced 1.28 MHz apart and averaged over 0.8 MHz. The y -axis ranges in arbitrary units are (left to right) 50–4620, 100–6000 and 100–1800. Celestial north is on top, and the red circles mark the size of the optical solar disc.

product of the electron number density and the component of the field in the direction of propagation.

The ability to routinely monitor and track CME magnetic fields would revolutionize the field of space weather. FR measurements have been in use for a while to characterize coronal plasma and CMEs. The first FR measurements of the coronal plasma were made by Stelzried et al. (1970) by tracking the changes in the plane of polarization of the telemetry signal from the Pioneer 6 spacecraft as it passed behind the Sun. Changes in FR associated with the passage of CMEs through the line of sight to spacecraft were convincingly detected using the telemetry signal from the Helios satellites (Bird 1982; Bird et al. 1985). More recently, coronal FR has been detected using VLA observations of radio galaxies as Sun passes in front of them (Mancuso & Spangler 2000; Spangler & Whiting 2009).

In addition to investigations of CMEs, FR measurements have also been used for many interesting studies of the nature of the solar corona and the solar wind; e.g. to determine the mean magnetic field in the corona (Patzold et al. 1987), to measure the power spectrum of coronal waves and turbulence as a function of distance (Efimov et al. 1996), to suggest the existence of intermittent waves at single locations (Chashei et al. 1999), to support theoretical models of wave dissipation as a coronal heating mechanism (Hollweg et al. 1982), and to study the structure of the heliospheric current sheet (Mancuso & Spangler 2000).

The FR studies so far have however been severely limited by the paucity of suitable sources of linearly polarized emission as the satellites pass through conjunctions very infrequently. In addition the comparatively high frequency (~ 1.4 GHz), small solar offsets ($\lesssim 10 R_{\odot}$, where R_{\odot} is the radius of the Sun), and the narrow fields of view of existing instrumentation limit the opportunities to do such work to a few times a year (Spangler & Whiting 2009). An effective tool for space weather prediction needs the ability to do routine monitoring of large numbers of los over a large range of solar offsets. This in turn requires large number of sources with linearly polarized emission, and as the observed $FR \propto \lambda^2$, moving to lower frequencies will increase the magnitude of the effect being measured. However, for cosmic sources, the fraction of polarized emission drops significantly at low frequencies. While that is true, observations using the Westerbork Synthesis Radio Telescope at 34–370 MHz have lead to detection of polarized extra-galactic sources exhibiting typical polarized intensities of 20 mJy and readily measurable RM (Wieringa et al. 1993; Haverkorn et al. 2003a,b,c). In the few areas of the sky investigated in detail reveal about one suitable polarized source every $\sim 4 \text{ deg}^2$; therefore these sources seem sufficiently numerous. In addition this work has also found large patches of diffuse polarized emission in the Galactic background with sufficient polarized flux.

The combination of the sensitivity of MWA, its low frequency of operation and wide field of view along with the availability of a large number of polarized sources with sufficient flux density present the exciting possibility of being able to measure the coronal

and heliospheric FR simultaneously to several different los and out to much larger solar offsets ($\sim 50 R_{\odot}$). No measurements of FR due to CME plasma are available yet at large solar offsets and one needs to rely on simulations to build quantitative expectations. Jensen et al. (2010) estimate the RM from CMEs to be $\sim 0.05 \text{ rad m}^{-2}$ (12° at 150 MHz) at about 0.4 AU. Liu et al. (2007) also arrive at a similar estimate and also show that the FR time series from instruments like the MWA during the CME passage may be used to infer the helicity and size of the CME.

For multiple reasons, these are rather challenging measurements to make. The most important of these, perhaps, are the needs for an accurate ionospheric calibration and high dynamic range. Ionospheric RM, is expected to usually be in the range $1\text{--}10 \text{ rad m}^{-2}$, more than an order of magnitude larger than the expected heliospheric or CME RM signature. This implies that we will need to achieve ionospheric RM calibration accuracies of a few percent over large fields of view in order to study heliospheric RM. The heliospheric or CME RM signature is expected to be detectable within say $50 R_{\odot}$ of the Sun. An optimistic value for polarized flux density of extragalactic sources close to the middle of MWA band is ~ 20 mJy and the quiet solar flux density is $10^4\text{--}10^5$ Jy. These observations hence need a polarimetric imaging dynamic range of about 10^6 , in the vicinity of a strong and variable Sun. However, in view of the large scientific and practical value of measuring the orientation of the magnetic field in a CME, we intend to pursue these measurements and hopefully demonstrate the ability to do this under favourable circumstances.

5.2.2 Interplanetary Scintillation

IPS is most easily described as the radio analog of optical twinkling of stars. As the radio waves from a distant compact radio source propagate through the turbulent and inhomogeneous solar wind plasma, the incident plane wavefronts pick up phase corrugations corresponding to these density inhomogeneities. These phase corrugations develop into intensity fluctuations by the time the wavefronts arrive at the Earth based telescope. Due to the motion of the solar wind, the interference pattern produced by these intensity fluctuations is swept past the telescope giving rise to the observed scintillations.

The evolution and dynamics of solar wind in the inner heliosphere dominates space weather effects. However, there are few techniques available to study the solar wind in this vast region. Historically IPS was the first remote sensing technique used to investigate the solar wind in this region (Hewish et al. 1964). IPS studies have traditionally been valued as providing the missing link needed to connect the observations at or close to the solar surface to those in the terrestrial neighborhood. More recently, routine availability of observations from heliospheric imagers that image very large parts of the heliosphere using white light scattered from the solar wind electrons, have emerged as a very useful tools for investigations in the inner heliosphere. This was pioneered by Solar Mass Ejection

Imager (SMEI) (Eyles et al. 2003) onboard the COROLIS satellite and the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) () instrumentation onboard the STEREO satellites represents the second generation of instrumentation. The spatial and temporal scales probed by IPS are much finer than possible using heliospheric imagers, and the details of the micro-level turbulence play an important role in heliospheric dynamics. These techniques, hence complement each other very well and have lead to a more complete characterization of the solar wind than would have been possible with either of the datasets (e.g. Jackson et al. 2007; Dorrian et al. 2008). The large scale sampling of the solar wind provided by IPS is also complementary to the very local *in-situ* sampling provided by most satellite based instrumentation.

There has recently been a resurgence of interest in IPS instrumentation. It is fueled by the desire of many groups across the world to exploit the recent technological developments to build the next generation of more capable instrumentation in order to enable new science opportunities. Apart from the MWA, the new IPS facilities coming up include the Low Frequency Array (LOFAR) in Europe (Bisi et al. 2011; Fallows et al. 2012) and Mexico Array Telescope (Mejia-Ambriz et al. 2010). In addition, the Ooty Radio Telescope in India (Manoharan, P. K., private communication) and Solar Wind Imaging Facility (SWIFT) in Japan (Tokumaru et al. 2011) are both undergoing considerable upgrades which will substantially improve their scientific capabilities.

As for any propagation effect, the IPS measurable represents an integral along the entire line-of-sight through the interplanetary medium (IPM). For the MWA, the primary IPS observable will be the power spectrum of observed intensity fluctuations, although we will also employ a less commonly used observable, the normalized co-spectrum obtained from simultaneous observations at frequencies differing by a factor of ~ 2 (Scott et al. 1983; Zhang 2007). Under the assumption of weak scattering, the IPM can be regarded as a collection of thin screens placed along the line-of-sight, and the IPS observable can be modeled as a weighted sum of the contributions from each of the thin screens. The physical parameters to which IPS is sensitive are: v - the velocity of the solar wind; Cn^2 - a measure of the level of electron density fluctuations (δn_e); α - the spectral index of δn_e ; q_i - the inner scale for the power law governing δn_e ; and AR - the axial ratio of δn_e . The ability to model IPS observables in terms of the physical attributes of the IPM, many of which are difficult to access by any other means, gives IPS its unique scientific strength.

Using an inversion process, it should be possible to extract the global 3D distribution of IPM parameters. Early work along these lines was done by (Jackson et al. 1998; Kojima et al. 1998; Asai et al. 1998; Oberoi 2000). Significant progress has since been made in refining this technique and applying it routinely to observations and has lead to some excellent comparisons of 3D structures identified using IPS with data from heliospheric imagers and other sources (e.g. Bisi et al. 2008, 2010; Dorrian et al. 2010; Xiong et al. 2011).

The most important bottleneck currently constraining the fidelity and resolution of inversion of IPS data, and hence its science output, are the sparseness (both in space and time) and the non-uniformity of the sampling of the heliosphere afforded by the present generation instrumentation (Oberoi & Benkevitch 2010).

The MWA will represent a significant advance in addressing the bottleneck of limited heliospheric sampling when its voltage capture system is completed. The MWA will have a sensitivity of ~ 70 mJy (1 second, 30.72 MHz) [**TBD: double check numbers**], comparable to that of the SWIFT transit facility currently under commissioning in Japan. The MWA will boost the number of independent IPS measurements by up to a factor of ~ 30 over what is possible with most present day systems. The southern hemisphere location of the MWA also complements the heliospheric coverage provided by the existing facilities, all of which happen to be in the northern hemisphere. The MWA will hence represent a significant step forward in enabling the science potential of IPS. Combining these data with other MWA observations like solar imaging and FR observations, and the observations from other sources like STEREO, SDO and HINODE, will provide a very comprehensive dataset for characterizing the inner heliosphere, monitoring and tracking CME evolution from close to the Sun to our terrestrial neighborhood. The software framework being developed for handling the MWA IPS data is being done with sufficient flexibility so that it may provide a common data repository, interface and analysis tools for IPS data from observatories across the world (Oberoi & Benkevitch 2010).

5.3 Ionospheric Science

Propagation through the dynamic and structured magnetoionic ionospheric plasma leaves an imprint on the incident low radio frequency radiation from astronomical sources. In order to arrive at the true properties of the incident radiation, the ionospheric distortion it has suffered must be identified and removed. The MWA tackles this long standing challenge by measuring the refractive shift in the apparent position of a few hundred bright and relatively compact sources, at a cadence of 8 s. The ionospheric calibration information thus comprises of a time series of vectors showing the refractive shift of calibrator sources from their fiducial positions. To first order, the magnitude of the shift is directly proportional to the relative ionospheric gradient in the total electron content (TEC) towards the fiducial sky position of the calibrator source. This information for all the observed calibrator sources leads to a series of differential TEC maps with a time resolution of 8 s and an accuracy of ~ 0.01 TECU. This map, produced routinely in real time as a part of the MWA calibration will form the primary data products for ionospheric science. The MWA beam will sample a region about $175 \text{ km} \times 175 \text{ km}$ at the F layer height of $\sim 300 \text{ km}$, and the expected calibrator source density corresponds to spatial scales $\sim 10 \text{ km}$ at this ionospheric height.

The high-precision and dense sampling of the iono-

sphere provided by the MWA offers new opportunities for ionospheric science. The three areas of ionospheric research that the MWA will make significant contributions are in: 1) the measuring of waves in TEC associated with traveling ionospheric disturbances (TIDs); 2) the development of sharp TEC gradients associated with space weather events during geomagnetic storm-time conditions; and 3) the tracking of the onset and evolution of scintillation associated with the development of ionospheric irregularities.

Traveling Ionospheric Disturbances – TIDs are manifestations of middle-scale ionospheric irregularities arising as response to acoustic gravity waves. TIDs are frequently observed at high and middle latitudes (Bristow et al., 1996, Nicolls and Heinselman, 2007, Oliver et al., 1994, 1997, Djuth et al, 2004), and their activity and amplitudes vary depending on latitude, longitude, local time, season, and solar cycle (e.g. Kotake et al., 2006, Hernandez-Pajares, et al., 2006). Large variations in both TID characteristics and propagation direction are not surprising, as they can be generated by distinct classes of processes, including auroral sources at the high latitude thermosphere, the passage of the solar terminator (Galushko et al. 2003), and storms, hurricanes and tornados in the troposphere. Detailed information about the sources, energetics, and scale sizes of energy coupling from the lower atmosphere to the upper atmosphere, along with resulting ionospheric effects, is critical to developing a deep understanding of overall upper atmospheric energy balance. Critical science topics in this area include gravity wave excitation mechanisms (Fritts and Alexander, 2003) and implications of observed gravity wave geographical and temporal variability (Allen and Vincent, 1995). TEC measurements are currently limited to be along the lines of sight to GPS satellites. The fine grid over which the MWA calibration solutions will provide differential TEC measurements will provide unprecedentedly detailed measurements of the propagation of TIDs over the array, and larger scale (> 10 km) TEC gradients and/or irregularities.

Space Weather Observations – The offset of the geographic and geomagnetic poles in the Australian sector, with attendant implications for neutral and ionized atmospheric coupling, places the MWA at a special longitude for investigating ionospheric space weather disturbances. Recent studies in the American sector, using the mid-latitude, wide field Millstone Hill ionospheric radar system at MIT Haystack Observatory, indicate that pole offset has important consequences in particular for the development of storm enhanced density (SED). The SED phenomenon (Foster, 1993) is responsible for some of the largest space weather effects at mid-latitudes (Coster and Foster, 2007) since it produces severe, temporally dependent electron density gradients. The geographic/geomagnetic pole offset in the southern hemisphere is similarly anticipated to influence the development of SED near the MWA (Coster et al., 2007; Foster and Coster, 2007; Foster and Erickson, 2012). SED associated gradients have a practical consequence, as they cause large errors in GPS range measurements, and significantly degrade the high precision positioning information provided by

GPS systems. Studying the effects of SED in the Australian longitude sector will advance many questions concerning the role of the offset of the poles. Additionally, MWA's longitude ($\sim 116^\circ\text{E}$) is very close to the longitude being extensively instrumented in the Asian sector as part of the Chinese Meridian project ($\sim 113^\circ$), and the conjugate longitude of $\sim 64^\circ\text{W}$ is within the field of view of the US sponsored chain of incoherent scatter radars, in particular Millstone Hill. The combination of simultaneous measurements from these distributed sensors thus provides a unique way to determine mesoscale response to geomagnetic disturbances in the coupled geospace system. In particular, it will be possible to investigate whether there is a seasonal and universal time dependence of geomagnetic storm response by comparing American and Asian/Australian sector response to solar wind and CME forcing. Such effects have been predicted theoretically (Foster and Erickson, 2012) but have not yet been confirmed by observations.

Ionospheric irregularities and scintillation – MWA observations using voltage capture capabilities will be uniquely suited for the exploration of ionospheric irregularities and scintillation. The availability of 32 array-beams which use the entire bandwidth and collecting area of the MWA, and which can be pointed independently anywhere within the wide MWA field-of-view, will provide scintillation measurements at multiple positions across the visible ionospheric region. MWA array-beam observations will be augmented by data from specially designed GPS receivers at and near the MWA site that can measure L-band scintillation statistics. GPS TEC data from these receivers, when combined with data from a large number of newly deployed GPS receivers on the Australian continent, will provide important contextual information about the regional distribution of TEC around the MWA site. Other satellite based remote sensing platforms, including COSMIC, DMSP, and JASON, will also be available during overflights to provide further information about background ionospheric plasma and electrodynamic conditions in the ionosphere.

6 Conclusion

The MWA is a unique low-frequency instrument with high survey efficiency and arcminute angular resolution. It will provide deep integrations on EoR target fields that could enable the first detection of the redshifted 21 cm signal and detailed characterization of diffuse Galactic emission and faint extragalactic source populations. The planned full-Stokes southern hemisphere sky survey will include the Galactic Centre, Galactic plane, and the Large and Small Magellanic Clouds, making the MWA particularly well-suited to identifying the missing population of SNRs, and thereby constraining the total energy budget of the Galaxy.

Long integrations in the EoR fields and regular observations along the Galactic plane will enable sensitive searches for pulsars and transient events on timescales from seconds to days. Blind surveys for both rare and faint events are planned, as well as targeted observa-

tions of known transient sources, including X-ray binaries, neutron stars, pulsars, and low-mass stellar objects.

The MWA will open new windows into space weather and solar physics and provide new measurements of solar bursts throughout their journey from the surface of the Sun to the Earth and on to the outer Solar System. High-dynamic range spectroscopic imaging will show the origin of bursts in the solar corona at heights of only a few solar radii, while monitoring of interplanetary scintillation will probe the interstellar wind. As events reach the Earth, the MWA's real-time calibration system will yield detailed measurements of ionospheric disturbances traveling over the telescope.

The telescope is complementary both to other new low-frequency radio telescopes, falling between LO-FAR and PAPER in both sensitivity and angular resolution. It is the only low-frequency SKA precursor and is located on the very radio-quiet site planned for the SKA low-band telescope. The combination of ASKAP and MWA at the MRO will yield a comprehensive program of pathfinder science for the SKA over the coming years. The MWA possesses a versatile design with excess infrastructure capability that will allow the telescope to and its users to embrace new scientific and technological opportunities over the coming decade, hopefully providing an enduring and fruitful future for the instrument.

Acknowledgments

This scientific work uses data obtained from the Murchison Radio-astronomy Observatory. We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatory site. Support for this work comes from the Australian Research Council (grant numbers LE0775621 and LE0882938), the National Science Foundation (grant numbers AST-0457585, AST-0821321, AST-0908884 and PHY-0835713), the U.S. Air Force Office of Scientific Research (grant number FA9550-0510247), the Australian National Collaborative Research Infrastructure Strategy, the Australia India Strategic Research Fund, the Smithsonian Astrophysical Observatory, the MIT School of Science, MIT's Marble Astrophysics Fund, the Raman Research Institute, the Australian National University, the iVEC Petabyte Data Store, the NVIDIA sponsored CUDA Center for Excellence at Harvard University, and the International Centre for Radio Astronomy Research, a Joint Venture of Curtin University of Technology and The University of Western Australia, funded by the Western Australian State government. The MRO is managed by the CSIRO, who also provide operational support to the MWA.

References

Amy, S. W., Large, M. I., & Vaughan, A. E. 1989, Proceedings of the Astronomical Society of Australia, 8, 172

- Antonova, A., Doyle, J. G., Hallinan, G., Golden, A., & Koen, C. 2007, *A&A*, 472, 257
- Asai, K., Kojima, M., Tokumaru, M., Yokobe, A., Jackson, B. V., Hick, P. L., & Manoharan, P. K. 1998, *Journal of Geophysical Research*, 103, 1991
- Asgekar, A., & Deshpande, A. A. 2001, *MNRAS*, 326, 1249
- Audard, M., Osten, R. A., Brown, A., Briggs, K. R., Güdel, M., Hodges-Kluck, E., & Gizis, J. E. 2007, *A&A*, 471, L63
- Baird, G. A., Meikle, W. P. S., Jelley, J. V., Palumbo, G. G. C., & Partridge, R. B. 1976, *Ap&SS*, 42, 69
- Balsano, R. J. 1999, Ph.D. thesis, Princeton University
- Bannister, K. W., Murphy, T., Gaensler, B. M., Hunstead, R. W., & Chatterjee, S. 2011, *MNRAS*, in press, 31, arXiv:1011.0003
- Barkana, R., & Loeb, A. 2005, *ApJ*, 624, L65
- Bastian, T. S. 2004, *Planetary and Space Science*, 52, 1381
- Bastian, T. S., Benz, A. O., & Gary, D. E. 1998, *ARA&A*, 36, 131
- Bastian, T. S., Dulk, G. A., & Leblanc, Y. 2000, *ApJ*, 545, 1058
- Bastian, T. S., Pick, M., Kerdraon, A., Maia, D., & Vourlidas, A. 2001, *ApJ*, 558, L65
- Becker, R. H., Helfand, D. J., White, R. L., & Proctor, D. D. 2010, *AJ*, 140, 157
- Belikov, A. V., & Hooper, D. 2009, ArXiv e-prints
- Benz, A. O., & Paesold, G. 1998, *A&A*, 329, 61
- Berger, E. 2006, *ApJ*, 648, 629
- Berger, E., et al. 2001, *Nature*, 410, 338
- Bhat, N. D. R., Cordes, J. M., Camilo, F., Nice, D. J., & Lorimer, D. R. 2004, *ApJ*, 605, 759
- Bird, M. K. 1982, *Space Science Reviews*, 33, 99
- Bird, M. K., et al. 1985, *Solar Physics*, 98, 341
- Bisi, M. M., Fallows, R. A., Jensen, E. A., Breen, A., Xiong, M., & Jackson, B. V. 2011, AGU Fall Meeting Abstracts, C2020
- Bisi, M. M., Jackson, B. V., Breen, A. R., Dorrian, G. D., Fallows, R. A., Clover, J. M., & Hick, P. P. 2010, *Solar Physics*, 265, 233
- Bisi, M. M., Jackson, B. V., Hick, P. P., Buffington, A., Odstreil, D., & Clover, J. M. 2008, *Journal of Geophysical Research (Space Physics)*, 113, 0
- Bower, G. C., Roberts, D. A., Yusef-Zadeh, F., Backer, D. C., Cotton, W. D., Goss, W. M., Lang, C. C., & Lithwick, Y. 2005, *ApJ*, 633, 218

- Bower, G. C., & Saul, D. 2011, *ApJ*, 728, L14
- Bower, G. C., Saul, D., Bloom, J. S., Bolatto, A., Filippenko, A. V., Foley, R. J., & Perley, D. 2007, *ApJ*, 666, 346
- Bowman, J. D., Morales, M. F., & Hewitt, J. N. 2006, *ApJ*, 638, 20
- Bowman, J. D., Morales, M. F., & Hewitt, J. N. 2009, *ApJ*, 695, 183
- Brentjens, M. A., & de Bruyn, A. G. 2005, *A&A*, 441, 1217
- Brogan, C. L., Gelfand, J. D., Gaensler, B. M., Kasim, N. E., & Lazio, T. J. W. 2006, *ApJ*, 639, L25
- Burgasser, A. J., & Putman, M. E. 2005, *ApJ*, 626, 486
- Burke-Spolaor, S., & Bailes, M. 2010, *MNRAS*, 402, 855
- Cairns, I. H. 2004, *Planetary and Space Science*, 52, 1423
- Cairns, I. H. 2011, *Coherent radio emissions associated with solar system shocks*, ed. Miralles, M. P. & Almedia, J. S. 267
- Cairns, I. H., Lobzin, V. V., Warmuth, A., Li, B., Robinson, P. A., & Mann, G. 2009, *ApJ*, 706, L265
- Cameron, P. B., et al. 2005, *Nature*, 434, 1112
- Camilo, F., Ransom, S. M., Halpern, J. P., & Reynolds, J. 2007, *ApJ*, 666, L93
- Camilo, F., Ransom, S. M., Halpern, J. P., Reynolds, J., Helfand, D. J., Zimmerman, N., & Sarkissian, J. 2006, *Nature*, 442, 892
- Cane, H. V., & Erickson, W. C. 2005, *ApJ*, 623, 1180
- Cane, H. V., Erickson, W. C., & Prestage, N. P. 2002, *Journal of Geophysical Research (Space Physics)*, 107, 1315
- Chakraborti, S., Ray, A., Soderberg, A., Loeb, A., & Chandra, P. 2010, *Nature*, in press, arXiv:1012.0850
- Charbonneau, D., Brown, T. M., Noyes, R. W., & Gilliland, R. L. 2002, *ApJ*, 568, 377
- Chashei, I. V., Bird, M. K., Efimov, A. I., Andreev, V. E., & Samoznaev, L. N. 1999, *Solar Physics*, 189, 399
- Chen, X., & Miralda-Escudé, J. 2004, *ApJ*, 602, 1
- Colgate, S. A., & Noerdlinger, P. D. 1971, *ApJ*, 165, 509
- Corbel, S., Kaaret, P., Fender, R. P., Tzioumis, A. K., Tomsick, J. A., & Orosz, J. A. 2005, *ApJ*, 632, 504
- Cordes, J. M., & Lazio, T. J. W. 2002, *astro-ph/0207156*
- Cordes, J. M., Lazio, T. J. W., & McLaughlin, M. A. 2004, *New Astronomy Review*, 48, 1459
- Cordes, J. M., & McLaughlin, M. A. 2003, *ApJ*, 596, 1142
- Cordes, J. M., Weisberg, J. M., Frail, D. A., Spangler, S. R., & Ryan, M. 1991, *Nature*, 354, 121
- Croft, S., Bower, G. C., Keating, G., Law, C., Whysong, D., Williams, P. K. G., & Wright, M. 2011, *ApJ*, in press, arXiv:1102.2227
- Datta, A., Bowman, J. D., & Carilli, C. L. 2010, *ApJ*, 724, 526
- de Oliveira-Costa, A., Tegmark, M., Gaensler, B. M., Jonas, J., Landecker, T. L., & Reich, P. 2008, *MNRAS*, 388, 247
- Deshpande, A. A., & Rankin, J. M. 1999, *ApJ*, 524, 1008
- Dessenne, C. A.-C., et al. 1996, *MNRAS*, 281, 977
- Donati, J.-F., Forveille, T., Cameron, A. C., Barnes, J. R., Delfosse, X., Jardine, M. M., & Valenti, J. A. 2006, *Science*, 311, 633
- Dorrian, G. D., Breen, A. R., Brown, D. S., Davies, J. A., Fallows, R. A., & Rouillard, A. P. 2008, *grl*, 35, 24104
- Dorrian, G. D., et al. 2010, *Solar Physics*, 265, 207
- Duncan, R. C., & Thompson, C. 1992, *ApJ*, 392, L9
- Efimov, A. I., Bird, M. K., Andreev, V. E., & Samoznaev, L. N. 1996, *Astronomy Letters*, 22, 785
- Eikenberry, S. S., Matthews, K., Munro, M., Blanco, P. R., Morgan, E. H., & Remillard, R. A. 2000, *ApJ*, 532, L33
- Eyles, C. J., et al. 2003, *Solar Physics*, 217, 319
- Fallows, R. A., Asgekar, A., Bisi, M. M., Breen, A. R., & ter-Veen, S. 2012, *Solar Physics*
- Fan, X., et al. 2006, *AJ*, 132, 117
- Farrell, W. M., Desch, M. D., & Zarka, P. 1999, *Journal of Geophysical Research*, 104, 14025
- Fender, R. 2006, in *Compact stellar X-ray sources*, ed. W. Lewin & M. van der Klis (Cambridge, UK: Cambridge University Press), 381
- Fender, R. P., Belloni, T. M., & Gallo, E. 2004, *MNRAS*, 355, 1105
- Fender, R. P., et al. 2006, in *VI Microquasar Workshop: Microquasars and Beyond*
- Field, G. 1958, *Proceedings of the IRE*, 46, 240
- Frail, D. A., Kulkarni, S. R., & Bloom, J. S. 1999, *Nature*, 398, 127

- Furlanetto, S. R., Oh, S. P., & Briggs, F. H. 2006, *Phys. Rep.*, 433, 181
- Furlanetto, S. R., Zaldarriaga, M., & Hernquist, L. 2004, *ApJ*, 613, 1
- Gaensler, B. M., et al. 2005, *Nature*, 434, 1104
- Galushko, V. G., Beley, V. S., Koloskov, A. V., Yampolski, Y. M., Paznukhov, V. V., Reinisch, B. W., Foster, J. C., & Erickson, P. 2003, *Radio Science*, 38, 060000
- Geil, P. M., Wyithe, J. S. B., Petrovic, N., & Oh, S. P. 2008, *MNRAS*, 390, 1496
- Ginzburg, V. L., & Zhelezniakov, V. V. 1958, *Soviet Astronomy*, 2, 653
- Grißmeier, J.-M., Zarka, P., & Spreuw, H. 2007, *A&A*, 475, 359
- Güdel, M. 2002, *ARA&A*, 40, 217
- Güdel, M., & Benz, A. O. 1993, *ApJ*, 405, L63
- Gupta, Y., & Gangadhara, R. T. 2003, *ApJ*, 584, 418
- Gurnett, D. A. 1974, *Journal of Geophysical Research*, 79, 4227
- Hallinan, G., et al. 2007, *ApJ*, 663, L25
- Halpern, J. P., Gotthelf, E. V., Becker, R. H., Helfand, D. J., & White, R. L. 2005, *ApJ*, 632, L29
- Hansen, B. M. S., & Lyutikov, M. 2001, *MNRAS*, 322, 695
- Haverkorn, M., Katgert, P., & de Bruyn, A. G. 2003a, *A&A*, 403, 1045
- Haverkorn, M., Katgert, P., & de Bruyn, A. G. 2003b, *A&A*, 403, 1031
- Haverkorn, M., Katgert, P., & de Bruyn, A. G. 2003c, *A&A*, 404, 233
- Hewish, A., Scott, P. F., & Wills, D. 1964, *Nature*, 203, 1214
- Hollweg, J. V., Bird, M. K., Volland, H., Edenhofer, P., Stelzried, C. T., & Seidel, B. L. 1982, *Journal of Geophysical Research*, 87, 1
- Hyman, S. D., Lazio, T. J. W., Kassim, N. E., & Bartleson, A. L. 2002, *AJ*, 123, 1497
- Hyman, S. D., Lazio, T. J. W., Kassim, N. E., Ray, P. S., Markwardt, C. B., & Yusef-Zadeh, F. 2005, *Nature*, 434, 50
- Hyman, S. D., Wijnands, R., Lazio, T. J. W., Pal, S., Starling, R., Kassim, N. E., & Ray, P. S. 2008, *ApJ*, submitted (arXiv:0811.1972)
- Inoue, S. 2004, *MNRAS*, 348, 999
- Ishwara-Chandra, C. H., Rao, A. P., Pandey, M., Manchanda, R. K., & Durouchoux, P. 2005, *Chinese Journal of Astronomy and Astrophysics Supplement*, 5, 87
- Jackson, B. V., Hick, P. L., Kojima, M., & Yokobe, A. 1998, *Journal of Geophysical Research*, 103, 12049
- Jackson, B. V., Hick, P. P., Buffington, A., Bisi, M. M., Kojima, M., & Tokumaru, M. 2007, *Astronomical and Astrophysical Transactions*, 26, 477
- Jenet, F. A., Anderson, S. B., & Prince, T. A. 2001, *ApJ*, 558, 302
- Jensen, E. A., Hick, P. P., Bisi, M. M., Jackson, B. V., Clover, J., & Mulligan, T. 2010, *Sol. Phys.*, 265, 31
- Johns-Krull, C. M., & Valenti, J. A. 1996, *ApJ*, 459, L95
- Johnston, S. 2003, *MNRAS*, 340, L43
- Johnston, S., Hobbs, G., Vigeland, S., Kramer, M., Weisberg, J. M., & Lyne, A. G. 2005, *MNRAS*, 364, 1397
- Kaiser, N. 1987, *MNRAS*, 227, 1
- Kaplan, D. L. 2008, *AIPC*, 983, 331, arXiv:0801.1143
- Kaplan, D. L., Hyman, S. D., Roy, S., Bandyopadhyay, R. M., Chakrabarty, D., Kassim, N. E., Lazio, T. J. W., & Ray, P. S. 2008, *ApJ*, 687, 262
- Kaplan, D. L., Kulkarni, S. R., Frail, D. A., & van Kerkwijk, M. H. 2002, *ApJ*, 566, 378
- Kaplan, D. L., Kulkarni, S. R., & van Kerkwijk, M. H. 2003, *ApJ*, 588, L33
- Kaplan, D. L., & van Kerkwijk, M. H. 2009, *ApJ*, 705, 798
- Karlický, M. 2003, *Space Science Review*, 107, 81
- Katz, C. A., Hewitt, J. N., Corey, B. E., & Moore, C. B. 2003, *PASP*, 115, 675
- Keane, E. F., & Kramer, M. 2008, *MNRAS*, 391, 2009
- Keane, E. F., Ludovici, D. A., Eatough, R. P., Kramer, M., Lyne, A. G., McLaughlin, M. A., & Stappers, B. W. 2010, *MNRAS*, 401, 1057
- Keith, M. J., et al. 2010, *MNRAS*, in press, 1356, arXiv:1006.5744
- Keller, S. C., et al. 2007, *Publications of the Astronomical Society of Australia*, 24, 1
- Keshet, U., Waxman, E., & Loeb, A. 2004, *New Astronomy Review*, 48, 1119
- Kojima, M., Tokumaru, M., Watanabe, H., Yokobe, A., Asai, K., Jackson, B. V., & Hick, P. L. 1998, *Journal of Geophysical Research*, 103, 1981
- Komatsu, E., et al. 2009, *ApJS*, 180, 330

- Kondratiev, V. I., McLaughlin, M. A., Lorimer, D. R., Burgay, M., Possenti, A., Turolla, R., Popov, S. B., & Zane, S. 2009, *ApJ*, 702, 692
- Kramer, M., Lyne, A. G., O'Brien, J. T., Jordan, C. A., & Lorimer, D. R. 2006, *Science*, 312, 549
- Kulkarni, S. R., & Phinney, E. S. 2005, *Nature*, 434, 28
- Kumar, S. S. 1962, *AJ*, 67, 579
- Lazio, T. J. W., & Farrell, W. M. 2007, *ApJ*, 668, 1182
- Lazio, T. J. W., Farrell, W. M., Dietrick, J., Greenlees, E., Hogan, E., Jones, C., & Hennig, L. A. 2004, *ApJ*, 612, 511
- Lenc, E., Garrett, M. A., Wucknitz, O., Anderson, J. M., & Tingay, S. J. 2008, *ApJ*, 673, 78
- Lidz, A., Zahn, O., McQuinn, M., Zaldarriaga, M., & Hernquist, L. 2008, *ApJ*, 680, 962
- Liu, A., Tegmark, M., Bowman, J., Hewitt, J., & Zaldarriaga, M. 2009, *MNRAS*, 398, 401
- Liu, A., Tegmark, M., & Zaldarriaga, M. 2009, *MNRAS*, 394, 1575
- Liu, Y., Manchester, W. B., IV, Kasper, J. C., Richardson, J. D., & Belcher, J. W. 2007, *ApJ*, 665, 1439
- Lobzin, V. V., Cairns, I. H., Robinson, P. A., Warmuth, A., Mann, G., Gorgutsa, R. V., & Fomichev, V. V. 2010, *ApJ*, 724, 1099
- Lonsdale, C. J., et al. 2009, *IEEE Proceedings*, 97, 1497
- Lyne, A. G., McLaughlin, M. A., Keane, E. F., Kramer, M., Espinoza, C. M., Stappers, B. W., Palliyaguru, N. T., & Miller, J. 2009, *MNRAS*, 400, 1439
- Macquart, J.-P. 2007, *ApJ*, 658, L1
- Mancuso, S., & Spangler, S. R. 2000, *ApJ*, 539, 480
- Marcy, G., Butler, R. P., Fischer, D., Vogt, S., Wright, J. T., Tinney, C. G., & Jones, H. R. A. 2005, *Progress of Theoretical Physics Supplement*, 158, 24
- Maron, O., Kijak, J., Kramer, M., & Wielebinski, R. 2000, *A&AS*, 147, 195
- Matsumura, N., et al. 2007, *AJ*, 133, 1441
- Matsumura, N., et al. 2009, *AJ*, 138, 787
- McClintock, J. E., & Remillard, R. A. 2006, in *Compact stellar X-ray sources*, ed. W. Lewin & M. van der Klis (Cambridge, UK: Cambridge University Press), 157
- McLaughlin, M. A., et al. 2006, *Nature*, 439, 817
- McLaughlin, M. A., et al. 2007, *ApJ*, 670, 1307
- McLean, D. J. & Labrum, N. R., ed. 1985, *Solar radio-physics: Studies of emission from the sun at metre wavelengths*
- McQuinn, M., Lidz, A., Zahn, O., Dutta, S., Hernquist, L., & Zaldarriaga, M. 2007, *MNRAS*, 377, 1043
- McQuinn, M., Zahn, O., Zaldarriaga, M., Hernquist, L., & Furlanetto, S. R. 2006, *ApJ*, 653, 815
- Mejia-Ambriz, J. C., Villanueva-Hernandez, P., Gonzalez-Esparza, J. A., Aguilar-Rodriguez, E., & Jeyakumar, S. 2010, *Solar Physics*, 265, 309
- Melrose, D. B. 1980, *Space Science Review*, 26, 3
- Melrose, D. B. 2003, *Plasma Physics and Controlled Fusion*, 45, 523
- Mirabel, I. F., & Rodríguez, L. F. 1999, *ARA&A*, 37, 409
- Mitchell, D. A., Greenhill, L. J., Wayth, R. B., Sault, R. J., Lonsdale, C. J., Cappallo, R. J., Morales, M. F., & Ord, S. M. 2008, *IEEE Journal of Selected Topics in Signal Processing*, vol. 2, issue 5, pp. 707-717, 2, 707
- Moortgat, J., & Kuijpers, J. 2005, in *Proceedings of the XXII Texas Symposium on Relativistic Astrophysics*, arXiv:gr-qc/0503074
- Morales, M. F., Bowman, J. D., & Hewitt, J. N. 2006, *ApJ*, 648, 767
- Morales, M. F., Hazelton, B., Sullivan, I., & Beardsley, A. 2012, *ArXiv e-prints*
- Morales, M. F., & Hewitt, J. 2004, *ApJ*, 615, 7
- Morales, M. F., Hewitt, J. N., Kasper, J. C., Lane, B., Bowman, J., Ray, P. S., & Cappallo, R. J. 2005, in *ASP Conf. Ser.*, Vol. 345, *From Clark Lake to the Long Wavelength Array: Bill Erickson's Radio Science*, ed. N. Kassim, M. Perez, W. Junor, & P. Henning (San Francisco: ASP), 512
- Nakar, E., & Piran, T. 2011, *ArXiv e-prints*
- Nelson, G. J., & Melrose, D. B. 1985, *Type II bursts*, ed. McLean, D. J. & Labrum, N. R. 333
- Nijboer, R. J., Pandey-Pommier, M., & de Bruyn, A. G. 2009, *SKA Memo #113*, <http://www.skatelescope.org/publications/>
- Nord, M. E., Henning, P. A., Rand, R. J., Lazio, T. J. W., & Kassim, N. E. 2006, *AJ*, 132, 242
- Noutsos, A., Johnston, S., Kramer, M., & Karastergiou, A. 2008, *MNRAS*, 386, 1881
- Oberoi, D. 2000, Ph.D. thesis, Indian Institute of Science
- Oberoi, D., & Benkevitch, L. 2010, *Solar Physics*, 265, 293

- Oberoi, D., & Kasper, J. C. 2004, *Planetary and Space Science*, 52, 1415
- Ord, S. M., Johnston, S., & Sarkissian, J. 2007, *Solar Physics*, 245, 109
- Osten, R. A., & Bastian, T. S. 2006, *ApJ*, 637, 1016
- Osten, R. A., Hawley, S. L., Bastian, T. S., & Reid, I. N. 2006, *ApJ*, 637, 518
- Palenzuela, C., Lehner, L., & Liebling, S. L. 2010, *Science*, 329, 927
- Pandey, M., Rao, A. P., Ishwara-Chandra, C. H., Durouchoux, P., & Manchanda, R. K. 2007, *A&A*, 463, 567
- Pandey, M., Rao, A. P., Pooley, G. G., Durouchoux, P., Manchanda, R. K., & Ishwara-Chandra, C. H. 2006, *A&A*, 447, 525
- Pandey, M. D., Rao, A. P., Manchanda, R. K., Durouchoux, P., Ishwara-Chandra, C. H., & Kulkarni, V. K. 2005, *Bulletin of the Astronomical Society of India*, 33, 382
- Parker, E. N. 1955, *ApJ*, 122, 293
- Patterson, C. D., Ellingson, S. W., Martin, B. S., Deshpande, K., Simonetti, J. H., Kavic, M., & Cutchin, S. E. 2008, arXiv:0812.1255
- Patzold, M., Bird, M. K., Volland, H., Levy, G. S., Seidel, B. L., & Stelzried, C. T. 1987, *Solar Physics*, 109, 91
- Popov, S. B., Turolla, R., & Possenti, A. 2006, *MNRAS*, 369, L23
- Readhead, A. C. S. 1994, *ApJ*, 426, 51
- Remillard, R. A., & McClintock, J. E. 2006, *ARA&A*, 44, 49
- Rickett, B. J. 1969, *Nature*, 221, 158
- Rickett, B. J. 1990, *ARA&A*, 28, 561
- Robinson, P. A., & Cairns, I. H. 2000, in *Radio Astronomy at Long Wavelengths*, ed. R. G. Stone, K. W. Weiler, M. L. Goldstein, & J.-L. Bougeret, 37
- Rogers, A. E. E., & Bowman, J. D. 2008, *AJ*, 136, 641
- Saar, S. H., & Linsky, J. L. 1985, *ApJ*, 299, L47
- Sagiv, A., & Waxman, E. 2002, *ApJ*, 574, 861
- Salah, J. E., Lonsdale, C. J., Oberoi, D., Cappallo, R. J., & Kasper, J. C. 2005, in *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference*, Vol. 5901, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, ed. S. Fineschi & R. A. Viereck, 124
- Santos, M. G., Cooray, A., & Knox, L. 2005, *ApJ*, 625, 575
- Scherer, K., Fichtner, H., Heber, B., & Mall, U., ed. 2005, *Space Weather: The Physics Behind a Slogan*.
- Schnitzeler, D. H. F. M., Katgert, P., Haverkorn, M., & de Bruyn, A. G. 2007, *A&A*, 461, 963
- Scott, D., & Rees, M. J. 1990, *MNRAS*, 247, 510
- Scott, S. L., Rickett, B. J., & Armstrong, J. W. 1983, *A&A*, 123, 191
- Shkolnik, E., Walker, G. A. H., & Bohlender, D. A. 2003, *ApJ*, 597, 1092
- Soderberg, A. M., et al. 2010, *Nature*, 463, 513
- Soderberg, A. M., et al. 2007, *ApJ*, 661, 982
- Spangler, S. R., & Whiting, C. A. 2009, in *IAU Symposium*, Vol. 257, *IAU Symposium*, ed. N. Gopalswamy & D. F. Webb, 529
- Stelzried, C. T., Levy, G. S., Sato, T., Rusch, W. V. T., Ohlson, J. E., Schatten, K. H., & Wilcox, J. M. 1970, *Solar Physics*, 14, 440
- Suzuki, S., & Dulk, G. A. 1985, *Bursts of Type III and Type V*, ed. McLean, D. J. & Labrum, N. R. 289
- Taylor, J. H., & Cordes, J. M. 1993, *ApJ*, 411, 674
- Thompson, C., & Duncan, R. C. 1995, *MNRAS*, 275, 255
- Tingay, S. J., Goeke, R., Bowman, J. D., Emrich, D., Ord, S. M., & et al. 2012, *Publications of the Astronomical Society of Australia* (submitted)
- Tokumaru, M., Kojima, M., Fujiki, K., Maruyama, K., Maruyama, Y., Ito, H., & Iju, T. 2011, *Radio Science*, 46, 0
- Tomsick, J. A., Corbel, S., Fender, R., Miller, J. M., Orosz, J. A., Tzioumis, T., Wijnands, R., & Kaaret, P. 2003, *ApJ*, 582, 933
- Usov, V. V., & Katz, J. I. 2000, *A&A*, 364, 655
- Vršnak, B., & Cliver, E. W. 2008, *Solar Physics*, 253, 215
- Warmuth, A., & Mann, G. 2004, in *Lecture Notes in Physics*, Berlin Springer Verlag, Vol. 656, *Lecture Notes in Physics*, Berlin Springer Verlag, ed. K. Scherer, H. Fichter, & B. Herber, 49
- Wieringa, M. H., de Bruyn, A. G., Jansen, D., Brouw, W. N., & Katgert, P. 1993, *A&A*, 268, 215
- Wild, J. P., Smerd, S. F., & Weiss, A. A. 1963, *ARA&A*, 1, 291
- Wilms, J., Pottschmidt, K., Pooley, G. G., Markoff, S., Nowak, M. A., Kreykenbohm, I., & Rothschild, R. E. 2007, *ApJ*, 663, L97
- Windhorst, R. A., Miley, G. K., Owen, F. N., Kron, R. G., & Koo, D. C. 1985, *ApJ*, 289, 494

- Woods, P. M., & Thompson, C. 2006, in *Compact stellar X-ray sources*, ed. W. Lewin & M. van der Klis (Cambridge, UK: Cambridge University Press), 547
- Wouthuysen, S. A. 1952, *AJ*, 57, 31
- Wu, C. S., & Lee, L. C. 1979, *ApJ*, 230, 621
- Wyithe, J. S. B. 2008, *MNRAS*, 387, 469
- Wyithe, J. S. B., & Loeb, A. 2008, *MNRAS*, 383, 606
- Wyithe, J. S. B., Loeb, A., & Barnes, D. G. 2005, *ApJ*, 634, 715
- Xiong, M., Breen, A. R., Bisi, M. M., Owens, M. J., Fallows, R. A., Dorrian, G. D., Davies, J. A., & Thomasson, P. 2011, *Journal of Atmospheric and Solar-Terrestrial Physics*, 73, 1270
- Zarka, P., Treumann, R. A., Ryabov, B. P., & Ryabov, V. B. 2001, *Ap&SS*, 277, 293
- Zaroubi, S., & Silk, J. 2005, *MNRAS*, 360, L64
- Zhang, X. 2007, *Chinese Journal of Astronomy and Astrophysics*, 7, 712