Astro2010: Solar and Heliospheric Physics with Low Frequency Radio Arrays

Prepared by

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About the authors: Drs. Kasper and Oberoi are the current and former chair of the Solar, Heliospheric, and Ionospheric (SHI) science consortium of the Murchison Wide-field Array (MWA), a low frequency radio array currently under construction in Western Australia under sponsorship from the NSF, AFOSR, and Australian agencies. Dr. Oberoi manages the MWA SHI science package and Dr. Kasper is Chair of the MWA Science Council.

1 Summary

This white paper presents outstanding fundamental questions about our Sun and its surrounding heliosphere that can be answered through the use of low frequency radio arrays (LFAs). The purpose of this white paper is to present these key questions, to motivate their urgency from the perspectives of fundamental plasma astrophysics and space weather effects on our climate and safety, and to make the case for a strong solar and heliospheric science component with current and future LFAs. LFAs are sensitive to both direct radio emission from coherent plasma processes in the solar corona and to the modification of radiation from background sources by the coronal and heliospheric plasma through Faraday Rotation (FR) and Interplanetary Scintillation (IPS). The greatly improved dynamic range, frequency coverage, and bandwidth of modern LFAs will open a new window on the physics of magnetic reconnection and particle acceleration at shocks. The combination of FR and IPS measurements of coronal mass ejections (CMEs) propagating from the corona through interplanetary space has the potential to revolutionize our understanding of how CMEs evolve and to predict the severity of their impact at Earth.

This white paper has been submitted both to the Stars and Stellar Evolution (SSE) Science Frontier Panel (SFP) and to the Cosmology and Fundamental Physics (CFP) in order to stress the inter-disciplinary and inter-agency support that would exist for development of future LFAs such as the Square Kilometer Array (SKA) with sufficient coordination between these communities.

This paper is organized as follows. Section 2 provides a brief background of heliospheric physics. Section 3 spells out the fundamental solar and heliospheric questions an LFA can address. Section 4 describes how LFAs can address these questions.

2 Our Dynamic Heliosphere

Deep within the Sun, possibly at the interface between the rigidly rotating core and the turbulent convection zone, the solar dynamo powers a twenty-two year cycle of magnetic activity. On the photospheric surface, the dynamo manifests itself through the eleven-year cycle of sunspots, cool regions where strong magnetic fields emerging from the interior prevent convection and limit the flow of heat. Driven by strong magnetic fields and the spectrum of large-scale motion, the solar atmosphere rapidly jumps in temperature above the photosphere in the narrow transition region to form the million degree solar corona. Within the corona, the eleven-year sunspot cycle corresponds to a flip in the direction of the global dipole magnetic field. The competition between the hot coronal plasma and the solar gravitational field is unstable, leading to the formation of the supersonic solar wind and the extension of the solar plasma into interplanetary space (Parker, 1958). Immersed within the extended solar atmosphere, Earth is magnetically coupled to the solar wind and with it to the solar dynamo.

The magnetic link between the solar corona and the geomagnetic field is one aspect of the Earth-Sun connection. There are benefits to living in the atmosphere of a star; the solar wind carves a magnetized bubble into the interstellar medium, more than one hundred AU in radius and extending far beyond Pluto, which blocks many galactic cosmic rays (Forbush, 1954). However, there are risks as well. The emergence of magnetic field – especially during periods of heightened solar activity – combines with the differential motion of the photosphere to drive the corona into increasingly unstable magnetic configurations. The sudden relaxation of the coronal magnetic field to a lower energy state is accomplished through explosive magnetic reconnection events that produce flares, eject millions of tones of coronal mass into interplanetary space, and accelerate particles to billions of electron volts. Solar energetic particles produce a radiation environment in interplanetary space and near Earth that is dangerous for spacecraft and humans (Dyer et al., 2003). The arrival of coronal mass ejections at Earth days after an eruption can trigger intense geomagnetic storms that disrupt communications and navigation and harm electrical power grids and oil pipelines (Lam et al., 2002).

It is important that we understand the forces that drive the Sun-Earth connection, from the evolution of the quiet solar wind over the solar cycle to the impact of solar eruptions on Earth.

3 Fundamental Questions

3.1 How does the solar coronal magnetic field change with time?

We know from observations of sunspots and direct measurements of the polarity and strength of magnetic field on the photospheric surface that the magnetic field of the Sun oscillates with a 22-year period of activity. The overall orientation of the Sun's magnetic field flips every 11-years, with the flip being accompanied by the emergence of strong sunspots that trigger intense solar flares and violent coronal mass ejections.

3.2 How does the coronal magnetic field extend into interplanetary space?

While we have detailed measurements of the magnetic field on the photospheric surface, we have little way of measuring the magnetic field in the corona and in interplanetary space other than by in situ measurements with spacecraft. The NASA Solar Probe spacecraft is a flagship mission to the inner heliosphere that would approach to within 9 solar radii of the surface of the Sun by the year 2018. Until this mission the closest field measurements have been by the Helios spacecraft at 0.3 AU. The measurements from these missions suffer from a fundamental limitation that they are from one point in space and therefore cannot be used distinguish between spatial and temporal variations in a model independent manner.

3.3 How do Coronal Mass Ejections erupt into the heliosphere?

Three-dimensional MHD simulations have slowly reached levels of sophistication where they can model the evolution of a CME as it moves through the heliosphere in detail (Manchester, 2005). The availability of relevant observations to guide and constraint these models, to help us distinguish the chaff from the substance, lag far behind. For a long time, once the CMEs moved out of the fields of view of the coronagraphs, there was no way to obtain any information about them as they propagate through most of an AU till they reached one of the spacecraft, usually at 1 AU and in the ecliptic plane. With the heliographic imagers on-board first SMEI (Jackson, 2004) and then STEREO (Howard, 2008), things have improved. The quality of data from these imagers has rapidly been improving. They observe the Thomson scattered white light from the CME electrons and can provide electron column density and bulk flow velocity, but are insensitive to the magnetic field strength and topology, and turbulence characteristics of the solar wind which determine much of the dynamic of evolution of the CMEs as they plough through the inner heliosphere. We do not however have a remote means of determining the structure of the magnetic field within the CMEs. Being able to measure the magnetic structure of a CME would permit us to study how the field within the CME is related to the original coronal field, and would allow us to predict the orientation of the field within CMEs that reach Earth.

3.4 How are particles accelerated by CMEs?

Optical and radio observations have shown that some CMEs can achieve speeds above 1000 km/s within several solar radii, forming strong shocks as upstream solar wind and coronal plasma is diverted around the CME (Gopalswamy, 2000). Under the right circumstances, the shock may also produce solar energetic particles (SEPs) by accelerating a portion of the local plasma to high energies. Gradual SEP events, characterized by slowly rising but ultimately intense SEP fluxes, have been associated with CMEs. The CME-driven shockwave are surprisingly efficient at converting the bulk energy of the CME into SEPs, with recent studies suggesting that as much as 20 percent of the total energy release in a CME has been observed to go into accelerating energetic particles (Emslie, 2004). We do not yet understand the acceleration of particles by CMEs, in particular the relationships between CME speeds, sizes, and geometries and the particles accelerated by the shocks they drive.

4 Answering these Questions

Section 3 described key fundamental questions about the Sun and the heliosphere. In this section we describe how LFAs can address these questions. As our guide, we use the planned capabilities of the Murchison Wide-field Array (MWA), an 8,000 element imaging interferometric radio array currently under construction in the Western Australian outback. MWA is one of several low frequency imaging arrays now under development including the Long Wavelength Array (LWA) in New Mexico and the Low Frequency Array (LOFAR) in Europe. Together, MWA, LWA, and LOFAR are technology pathfinders that aim to show how modern computing and information technology capabilities such as high performance Field Programmable Gate Arrays (FPGAs) devices, high bandwidth data transfer networks, low power massively parallelized computing systems, and digital image processing will enable a generation of LFAs with unprecedented imaging capabilities and the ability to transcend the ionospheric barrier. Ultimately if these pathfinders are successful they will lead the way to the SKA, an LFA with even higher sensitivity, resolution and fidelity.

In order to appreciate this sudden burst of array construction it is useful to review the history of low frequency radio imaging. The 1970s and early 1980s were a golden age for low frequency radio studies of the solar corona (See Kassim et al. 2006 for an extensive review of this period). Instruments such as the Clark Lake TPT array and the Culgoora Radioheliograph provided new observational discoveries that drove research on the physics of solar radio emission and contributed to our understanding of fundamental solar processes. By the mid-1980s, however the field of low frequency imaging began to stagnate. The Clark Lake facility was dismantled, and while new arrays such as the Nancay Radioheliograph operate at low frequencies, there has been little in the way of real technological innovation in the intervening two decades. This is not for lack of compelling science that can be done with low frequency radio imaging (e.g. Bastian 2004; Cairns 2004; Oberoi & Kasper 2004). Progress in low frequency imaging was prevented by the barrier imposed on imaging fidelity by electron density fluctuations in the ionosphere. Fluctuations in the total electron column density (TEC) in ionosphere distort the radio wavefront from the celestial sources. This distortion is time and direction dependent and can change from antenna to antenna if the antenna separation approaches or exceeds the ionospheric Fried length scale. If uncorrected, these distortions lead to an impact much like the scintillation of stellar images due to Earth's atmosphere, and lead to blurred images. The recent advances in low frequency radio imaging are the analog of adaptive optics systems for large optical telescopes, which *undo* the ionospheric distortion in real time allowing one to reap the benefits of higher resolution (longer baselines for the case of radio) and higher sensitivity (larger collecting area and increased integration time). Even though the problem of ionospheric de-distortion could be mathematically well posed, it required computational power which was far beyond what was available then. In the 1990s a new ionospheric correction capability resembling adaptive optics was finally demonstrated with the 74 MHz extension of the VLA, prompting a resurgence in low frequency arrays (Cohen et al. 2006). Essentially, with sufficient sensitivity (or collecting area), bright sources in the field of view are monitored and their refraction due to ionospheric irregularities is measured. Refraction across the entire field of view is then determined by interpolating between the bright calibrator sources. With their large fields of view, large collecting area, and significant real-time computing and imaging capabilities, these new arrays are optimized to employ the adaptive optics technique to break the confusion limit previously imposed by the ionospheric barrier (Lonsdale 2005).

4.1 Faraday Rotationu

Faraday Rotation (FR) is a dispersive property of magnetized plasmas that results in the rotation of linearly polarized radio waves. Emission of wavelength λ rotates by an angle $\phi = \lambda^2 RM$, where the Rotation Measure (RM) is proportional to the integral of the product of the electron number density n_e and the component of the magnetic field field $\vec{B}$ in the propagation direction. With SI units, RM is given by,

$$RM = 2.6 \times 10^{-13} \int n_e(s) \vec{B} \cdot d\vec{s}. \qquad [rad\ m^{-2}]$$

FR observations with a LFA capable of monitoring a wide field of view surrounding the Sun are the only known technique which has the potential to provide information about the heliospheric magnetic field in the vast inner heliosphere region. FR due to plasma in the solar corona was first detected by tracking variations in the polarization angle of the telemetry signal from the Pioneer 6 spacecraft as it passed behind the Sun (Stelzried, 1970). If the orientation of the antenna on the spacecraft is known, and the transmissions are linearly polarized, then a ground tracking station may measure the arrival angle of the telemetry signal and deduce the rotation. Typical values of the RM observed due to the quiet corona were about $100\, rad\, m^{-2}$ at $5\, R_\odot$ and $10\, rad\, m^{-2}$ at $10\, R_\odot$. Similar measurements, generally utilizing signals in the GHz range, have been performed by tracking other spacecraft such as Helios with the DSN (Bird, 1982). More recently, coronal FR has been detected by tracking radio galaxies with a dedicated telescope such as the Very Large Array (VLA) as the Sun passes in front of them Mancuso, 2000).

The data from these observations have been used for many studies of the nature of the solar corona and the solar wind. The Helios data were used to determine the mean magnetic field in the corona (Patzold, 1987). FR measurements have been used to measure the power spectrum of coronal waves and turbulence as a function of distance (Efimov, 1996) and to suggest the existence of intermittent waves at single locations (Chashei, 1999). These measurements have been used to support theoretical models of wave dissipation as a coronal heating mechanism (Hollweg, 1982). More recent observations have grown in sophistication, for example, by using the VLA to monitor several galaxies over the course of two weeks, and these results were used to study the structure of the heliospheric current sheet (Mancuso, 2000). A particularly interesting FR measurement is the result by Bird (1985), who detected the passage of a coronal mass ejection between Helios and Earth. The time for the CME to pass between the spacecraft and Earth was predicted using a sequence of coronograph images, and within several minutes of the predicted time the RM changed sharply, due to the passage of the ejecta. These observations proved that CMEs can produce detectable FR signal significantly stronger than the quiet heliosphere. Recently, Liu (2007) has shown that the FR time series seen by Helios during the CME passage could have been used to determine the helicity and size of the CME.

While FR observations clearly have a broad range of applications, the measurements to date have suffered from several large limitations. The number of sources is severely constrained, either due to the small number of spacecraft passing behind the Sun or in the case of a telescope such as the VLA the narrow FOV of the instrument combined with the expense of dedicated observing time. The RM of the ionosphere itself, typically ranging between $1-8\, rad\, m^{-2}$ at noon solar min to solar max places a lower limit on the solar RM that can be measured without understanding and calibrating out the ionospheric contribution. The Bird (1985) detection of a CME was limited because the RM eventually grew so large that polarization angle of the Helios signal rotated by more than 180° and became ambiguous. This over winding is a serious challenge for FR observations at a small number of frequencies. New LFAs with wide fields of view and the ionospheric calibration capability described at the start of Section 4 can significantly advance the utility of FR observations by accurately tracking changes in the FR from polarized background objects including extragalactic objects, pulsars, and diffuse emission from our own galaxy. For optimum performance the LFA would feature sufficient frequency and angular resolution to avoid bandwidth and beam depolarization of the background sources.

4.2 Interplanetary Scintillations

IPS is the radio analogue of optical twinkling of stars due to the turbulence in the Earth's atmosphere. To the low frequency radio waves, the solar wind appears as a medium with fluctuating refractive index. As a plane wavefront from a distant compact radio source passes through this medium, it picks up corrugations which develop into intensity fluctuations by the time they reach the Earth. The bulk flow of the solar wind causes this interference pattern to be swept across the telescope leading to observations of fluctuating intensity, or IPS.

As with all propagation effects, IPS observables are line-of-sight (LoS) integrals. They can be modeled in the weak scattering regime to yield primarily the velocity, fluctuations in the electron number density and the turbulence power law index (Kolmogorov index). IPS techniques have been in use for past four decades to study the solar wind. Their application has been limited by the fact that the number of free parameters needed to model the solar wind plasma along a LoS usually far exceeds the number of constraints provided by individual or a few IPS observations. In their original form, IPS studies have usually been limited to situations where the solar wind can be described using comparatively few free parameters, e. g. quiet solar wind conditions or transients strong enough to dominate the measurable along the entire LoS. Any attempts at meaningful enhancement of this technique must significantly increase the number of constraints from observations. The UCSD and STELab groups have pursued this approach and have attempted tomographic reconstructions of the inner heliosphere by self-consistently inverting IPS data collected over a solar rotation. Their efforts have met with the most success in mapping the quiet solar wind and a few strong interplanetary events (Jackson et al., 1998; Kojima et al., 1998).

The MWA digital array beamformer provides 32 simultaneous independent beams. This will allow MWA to monitor 32 different IPS sources simultaneously. In addition, the higher sensitivity of MWA will increase the number of accessible sources in the sky to or order 1000 from about 40 for the STELab facility, the current leading dedicated IPS instrument. This large increase in the number of observations directly addresses the most severe problem of insufficient number of constraints and is expected to significantly enlarge the regime of validity of IPS inversion methods. Future LFAs with digital beamforming technology for other purposes, such as pulsar timing, could also be used during the day to conduct these solar and heliospheric IPS observations.

4.3 Radio Bursts

Solar radio bursts are manifestations of macroscopic release of energy in CMEs, solar flares and other evolving magnetic structures. They are believed to be caused by shocks and energetic electrons moving through the solar corona into the interplanetary medium. Much effort has been invested in observing, cataloging and understanding the characteristics of these bursts since their first detection in the early 1940s. This has lead to considerable progress in understanding of the subject and an extensive body of literature as illustrated in the recent reviews by Bastian et al. (1998), Robinson and Cairns (2000), Cairns and Kaiser (2002) and Gopalswamy (2004). In this white paper we focus on how LFAs can address Type II bursts. Type II bursts are often grouped into metric (m), decametric/hectometric (DH) and kilometric (km), depending on the wavelength regime in which they are observed. While it is generally accepted that DH and km type IIs are caused by CME driven shocks (Sheeley et al., 1985), the nature of energy source for the m-type II bursts is still controversial (see Gopalswamy et al., 1998; Cliver et al., 1999; Cairns and Kaiser 2002 for recent reviews).

While all m-type II bursts seem to be associated with flares, only a few of the flares are associated with m-type II bursts. Similarly m-type II bursts have a very strong association with CMEs, though the converse is not true. There are reasons to believe that type II bursts are associated with fast CMEs (Gopalswamy et al., 1997, 1999; Cliver et al., 1999; Klien 1999). The qualifier fast implies that the CME should be traveling fast enough to drive a shock, i.e. its speed should exceed the fast mode speed in the ambient medium (Gopalswamy, 2004). The proponents of this argument explain the lack of a perfect correlation between m-type IIs and CMEs by pointing out that some CMEs may escape detection by the available instrumentation (Cliver et al., 1999). The skeptics, on the other hand, argue that some of the flares for which corresponding CMEs could not be located have been so bright (class X4) that the corresponding CMEs, had they existed, would be significantly above the detection threshold of instruments like the LASCO coronagraph even if they were to be directed diametrically away from the Earth. For the few cases where positional information is available for type II bursts, the radio source seems to occur well behind the leading edge of the CME (Wagner and MacQueen, 1983; Gary et al., 1984; Robinson and Stewart, 1985). This runs contrary to the idea of CME driven shocks, unless the emission originates only from the flanks of a CME driven shock. The competing scenario for energizing m-type IIs is using flare blast waves, i.e. they are caused by sudden heating of the coronal loops during flares. While it is consistent with the short life times of the bursts (Bougeret, 1985; Vrsnak, 1995; Gopalswamy et al., 1998) the primary difficulty with this model is that it does not produce any observable signature other than the m-type II burst itself.

Since the closure of Culgoora and Clark Lake observatories more than 20 years ago, radio images of burst emission have not been available. The 150-450 MHz frequency coverage of the Nançay Radio Heliograph in France has a poor overlap with the m-type II spectral regime which are usually observed at frequencies below 150 MHz. The Gauribidanur Radio Heliograph in India offers the right frequency coverage (40-150 MHz) but is limited in frequency agility, bandwidth (1 MHz) and baseline lengths (1.28 km East-West and 0.44 km North-South) (Ramesh, R. et al., 1998) and is not efficient at imaging m-type II bursts which typically last for 5 to 15 min and have a frequency drift rate of around -0.16+/-0.11 MHz/sec (Mann et al., 1996). All investigations of solar burst emission currently rely solely on their dynamic spectra (frequency time plane plots of intensities). If imaging observations with future LFAs could be brought to bear on this problem, progress can be made on many of the currently open questions. For instance, the relative locations of the burst emission and the CME front will help in clarifying the relationship between radio bursts, CMEs, flares and magnetic reconnection. The observed angular size of the emission and its variation with frequency will provide information about source structure and scattering properties in the inner corona.