Long-Term Datasets for the Understanding
of Solar and Stellar Magnetic Cycles
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Solar science at metric radio wavelengths: Coming of age

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The merits of solar coronal at metric-wavelength (MW) radio have long been recognised (e.g. Pick and Vilmer, 2008). High-fidelity solar radio imaging at these frequencies has however remained challenging. On the one hand, dealing with the small spectral and temporal scales of variation in solar radio emission requires a data product capable of tracking the emission simultaneously across time, frequency and morphology. The Fourier imaging nature of interferometry, on the other hand, severely limits the instrumental ability to gather sufficient information to do this with the required fidelity and resolution. Benefiting from the enormous advances in technology the new generation of instruments, like the Murchison Widefield Array (MWA; Tingay *et al.* (2013), Bowman *et al.* (2013)), represent a quantum leap in our ability to gather data suitable for radio solar physics.

Though the radio instruments have recently become much more capable, and despite their considerable merits, the use of radio data in solar physics is yet to become mainstream. In many ways, on technical fronts, the problem has shifted from the limited intrinsic information content of the data available earlier to our ability to extract the required information from the vast data volumes produced by new generation instruments. This necessarily requires grappling with the issues not only of algorithmic complexity and human effort involved in analyses of these data, but also those related to their transport, storage and computational demands. This is further compounded by the facts that, for historically valid reasons, radio interferometry in general, and solar radio interferometry to an even larger extent carries the reputation of being a rather specialised area with a steep learning curve; and globally the number of practicing solar radio astronomers is rather small. We recognise that providing essentially science-ready radio data products, analogous to what is often available at other wavebands, is an essential requirement for making the use of radio diagnostics more mainstream. Towards this long-term objective, we have systematically been working on building an in-depth understanding of the MWA data and developing the necessary analysis algorithms and pipelines for enabling solar science with these data products. Here, we briefly summarise the current status of our efforts.

We have been working on developing the necessary algorithms and pipelines and also using them for specific science applications. The choice of our work has been optimised to benefit from the strengths of the MWA design, namely its sensitivity to weak emissions, low radio frequency interference environment and unprecedented spectroscopic imaging capability; and the low level of solar activity during our observations. On the techniques and algorithms front, our first need was to associate a flux scale with MWA solar observations. For this, we developed a robust and computationally lean non-imaging flux calibration technique which uses less than 0.1% of the total interferometric dataset (Oberoi *et al.*, 2017). We have also developed the necessary framework to transfer this calibration to solar radio images and the 4D brightness temperature (T_B) datacube ($T_B(\theta, \phi, t, \nu)$), which captures all the information there is in the interferometric data (Mohan and Oberoi, 2017). We are now in the process of developing a solar interferometric imaging pipeline (Mondal *et al.*, 2018). The imaging dynamic range of images from this pipeline lies in the range from $\sim 10^3$–10^5. This exceeds the dynamic range of the earlier state-of-the-art by between one and two orders of magnitude, and often matches or exceeds that of EUV or X-ray images from space-based observatories.

Using these tools and others, we have carried out various imaging and non-imaging science investigations. Studies of weak short-lived narrow-band, and hence nonthermal, emissions have been an area of emphasis. We used a wavelet-based technique to identify and characterise the nature of these nonthermal emissions in the MWA dynamic spectra (DS) (Suresh *et al.*, 2017). Using a Gaussian mixtures based approach, we have for the first time, quantified the flux density and prevalence of weak ($\sim$0.2 SFU; 1 Solar Flux Unit = 10^4 Jy) nonthermal emissions observed in the DS (Sharma *et al.*, 2018a). A brief description of these investigations is available in Sharma *et al.* (2018b). A natural extension of this work is to look for evidence of nonthermal emissions in the image plane and our analysis suggests their presence at 0.1 mSFU level, making these by far the weakest nonthermal solar radio emission to be reported (Sharma and Oberoi, 2018, in preparation). Many of our recent imaging studies have focused on type III solar radio bursts. One of them shows SDO UV-EUV observations of strong upwards and downwards pairs of jets, current sheets, cusp-like features on loop tops, and outflows along open magnetic field lines that are consistent with type IIIs imaged using the MWA (Cairns *et al.*, 2018). Another study shows repetitive splitting of type III sources that diverge at speeds $\sim$0.3c, consistent with SDO EUV observations of open field lines above a quasi-separatrix layer and a coronal null point associated with a 3D magnetic reconnection (McCauley *et al.*, 2017). An ongoing study demonstrates the ability of such radio observations to reveal the detailed dynamics of type III radio sources (Mohan *et al.*, 2018).

We conclude by noting that radio observations can provide novel indices of solar activity at a range of coronal heights not easily accessible to other wavebands. The near-future availability of better tools and data products will hopefully lead to their being recognised as useful indices; and initate efforts for long term radio imaging monitoring.

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