Waves in the sky: Probing the ionosphere with the Murchison Widefield Array

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Low-frequency, wide-field radio telescopes such as the Murchison Widefield Array (MWA) enable the dense spatial sampling of the ionosphere and plasmasphere on regional scales. For a physically compact array such as the MWA, the refractive shifts in the positions of celestial sources in the synthesised radio images are proportional to spatial gradients in the total electron content (TEC) transverse to the line of sight. By measuring the angular position shifts of celestial radio sources, one can probe waves and disturbances in the intervening plasma. Radio telescopes differ fundamentally from other techniques for measuring plasma fluctuations in that they are sensitive to TEC gradients/differences rather than absolute TEC. This makes them sensitive specifically to fluctuations about the ambient density, and therefore powerful probes of plasma density waves and irregularities.

We present the results of an analysis of plasma fluctuations detected by the MWA, which can measure TEC gradients to a precision of ~1 mTECU/km at observing frequencies of ~150

MHz. Around 2000-3000 point sources are visible instantaneously to the MWA, each functioning as a measurement point for the TEC gradient across the field-of-view (FoV). The spatial sampling completeness achieved by the MWA is unparalleled among interferometer observations of the ionosphere/plasmasphere to date, which have been limited both to smaller fields of view and at most several tens of measurement points (e.g. J. F. Helmboldt, W. M. Lane & W. D. Cotton, 2012, *Radio Sci.*, **47**, RS5008). This ~100-fold improvement in sampling completeness has permitted the first detailed imaging of the near-Earth plasma by a radio telescope.

Most of the fluctuations detected in MWA data are transient, with the spatial and temporal properties of travelling ionospheric disturbances. An intriguing phenomenon recurring above the site of the MWA are regularly-spaced bands of plasma strongly elongated along the geomagnetic field. These can occur in huge numbers (10-20 per MWA FoV), persist for long durations, drift slowly across the sky, and are sometimes associated with scintillations of radio sources. Such field-aligned density structures may be those responsible for guiding the propagation of whistler waves to the ground. They are possibly related to the phenomenon discovered by Jacobson & Erickson (1993, *Ann. Geophys.*, **11**, pp. 869-888) of nearly-corotating plasmaspheric tubes that appear as overdensities and underdensities alternating with magnetic longitude. Our results represent the first ground-based imaging of these structures, testimony to the exquisite sensitivity and novelty of next-generation radio telescopes as probes of the geoplasma environment.