

# Report on Potential Usage of SKA1-Low by Canadian Astronomers

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The goal of this document is to demonstrate the range of science and science leadership envisioned for Canadian astronomers using the planned SKA1-Low component of the Square Kilometre Array (SKA) telescope. The SKA1-Low telescope will be located at Murchison Radio-astronomy Observatory in Western Australia. According to the rebaselining specifications of Feb. 2016, it will consist of about 130,000 antenna elements operating from 50 MHz to roughly 350 MHz, with a sensitivity of about 500 m<sup>2</sup>/K. The field of view will be about 20 deg<sup>2</sup> with multiple beams.

Canadian scientists have expertise in a number of areas that will benefit from this instrument, and there is considerable excitement at the prospect of this component of the SKA1 telescope. Here we outline some of the major topics to be explored.

**Pulsars:** Pulsars have steep spectral indices but also suffer from increased interstellar dispersive smearing at the low radio frequencies at which they are bright. Searches for new pulsars must therefore trade off between these phenomena. The SKA1-Low will be a superb instrument for finding pulsars, including exotic and relativistic binaries, out of the Galactic Plane, and a deep, efficient all-sky survey for  $|b| > 5 \text{ deg}^\circ$  is one of the major projects planned for this telescope (Keane et al. 2015, Proceedings of Science; arXiv:1501.00056). Canadian astronomers have a long history of involvement in radio pulsar surveys at Parkes, Green Bank and Arecibo (e.g., Scholz et al. 2015, ApJ **800**, 123) as well as leadership in the study of relativistic binaries (e.g., Fonseca et al. 2014, ApJ **787**, 82) and are eager to use the SKA1-Low for these purposes. The SKA1-Low can also contribute monitoring of dispersion and scattering variations to the long-term project of detecting gravitational waves using millisecond pulsar timing (Janssen et al. 2015, Proceedings of Science; arXiv:1501.00127). With their ongoing participation in the NANOGrav pulsar timing array collaboration and imminent development of expertise in tracking interstellar medium variations with the CHIME telescope, Canadian pulsar astronomers are well-positioned to play a leading role in this science.

Pulsar scintillometry uses the interstellar medium (ISM) to map the pulsar magnetospheres (Pen et al. 2014, MNRAS **440**, 36), and pulsars to map ISM structure, with pulsar scintillation arcs interpreted as reconnection sheets in the Toronto picture (Pen and Levin 2014, MNRAS **442**, 3338). The Faraday rotation change across the scattering screen is expected to be measured in the SKA-low band, giving direct access to the small scale magnetic field structures in the ISM. Proposed applications include precise distance measurements for improved PTA sensitivity and precision gravitational wave localization (Boyle and Pen 2012, PRD, **86**, 124028), pulsar mass measurements, and more. Scintillation is an intrinsically low frequency phenomenon, where SKA-LOW will revolutionize the sensitivity. Jointly with GMRT-VLBI, this enables the precision mapping of pulsars and the ISM. Canada is the world leader in this effort.

**Transients:** The SKA1-Low instrument will be sensitive to fast radio transients such as the still-enigmatic Fast Radio Bursts (FRBs). Canadians are keenly involved in this exciting new field (e.g., Masui et al. 2015, Nature **528**, 523; Scholz et al. 2016, ApJ **833**, 177). Canadian astronomers have recently shown that there are no FRBs detected in 61 days of search-mode data taken with the Green Bank Telescope at 350 MHz (Chawla et al., ApJ, submitted; arXiv:1701.07457). Thus FRBs must have either shallow spectra or a low-frequency turnover, which implies that any low-frequency FRBs will be at high redshift, and therefore the dispersion measures and overall rate will be especially important and interesting. The large number of FRB detections anticipated with the CHIME telescope will inform expectations for the number to be detected with SKA1-Low.

Imaging studies of "slow" (longer than second timescales) transients at low radio frequencies will be of great interest to Canadian astronomers. The large field of view and excellent sensitivity of SKA1-Low will provide commensal monitoring (on timescales of seconds to years) of slow transients such as relativistic jets of black hole X-ray binaries in outburst. Canadian astronomers recently developed a new model for jet ejections to explain rapid radio-millimeter lightcurves tracked during the 2015 outburst of V404 Cygni (Tetarenko et al., MNRAS, submitted) and will take full advantage of SKA1-Low data available for future outbursts. Combining these data with similar data from optical and X-ray all-sky monitors will provide a daily view that connects the physics of accretion disks and the launching of relativistic jets. Similarly radio flares from magnetars like SGR 1806-20 will also (commensally) probe relativistic ejecta, albeit in much stronger magnetic regimes, such as in the pioneering work of Gaensler et al. (2005, Nature **434**, 1104). Since the results of bright impulsive synchrotron events will tend to peak at later times and lower flux densities at lower frequencies, targeted observations of bright (and even late-detected) GRB afterglows can be used to constrain properties like the energy distributions in electrons and magnetic fields and the density of the ambient medium, in concert with earlier multiwavelength observations.

**Cosmic Magnetism:** Magnetism science for SKA1-Low is primarily focused on three areas: (1) the magnetic field in clusters, filaments and the cosmic web; (2) broadband polarimetry as a probe of AGN; and (3) emergence of magnetic fields in the Universe. Canada has strong interest and expertise in all these areas, for SKA pathfinder and precursor experiments (VLASS, POSSUM, GLEAM) and for the SKA itself.

For (1), Canadian astronomers have used the MWA to publish the deepest ever limits on the synchrotron cosmic web (Vernstrom et al. 2017, MNRAS, in press, arXiv:1702.05069), and plan to use this pilot project as a stepping stone to much deeper experiments with MWA Phase 2 and with SKA1-Low. For (2), Canadians have published by far the largest ever catalogue of extragalactic rotation measures (Taylor, Stil & Sunstrum 2009, ApJ **702**, 1230; 37000 sources) and the definitive all-sky map of Faraday rotation measures (Oppermann et al. 2012, A&A **52**, 93; 2015, A&A **575**, 118). Canadians have set out the core science case for upcoming broadband studies (Gaensler et al. 2015, Proceedings of Science; arXiv:1501.00626), and are developing the software pipeline to process data from the POSSUM and VLASS programs. For (3), Canadians have published the largest ever samples of high-redshift rotation measure data (Hammond, Robishaw & Gaensler 2012, arXiv:1209.1438v3; Vernstrom et al., in preparation), and plan to extend these studies with MWA, VLASS, ASKAP, and then SKA1-Low. This is accompanied by strong theoretical expertise in magnetogenesis (e.g., Widrow 2002, Rev. Mod. Phys. **74**, 775; Widrow et al. 2012, ApJ **75**, 41).

**Cosmology and the Epoch of Reionization:** Neutral hydrogen emits and absorbs 21cm light that is redshifted to longer wavelengths. Since most ordinary matter in the universe is composed of hydrogen, mapping the intensity of redshifted 21cm light across the sky provides a 3-dimensional map of matter and a measure of its ionization fraction. The hydrogen intensity mapping technique was pioneered by a team co-led by Canadian astronomers using the Green Bank Telescope (Chang et al. 2010, Nature **466**, 463) and is a flagship science target for SKA1-low. Indeed, Canadian Astronomers are capitalizing on this technique at higher frequency by building the CHIME telescope (Bandura et al. 2014, SPIE Proceedings, arXiv:1406.2288) and using it to study Dark Energy. Cosmology is a key area of strength for Canada and the community across Canada is eager to obtain the capabilities of the SKA to probe the cosmos at lower frequency than CHIME can provide.

21cm intensity mapping emission arises from the collective neutral hydrogen in galaxies and potentially self-shielding clouds. Mapping this emission over cosmic time shields light on the cosmic galaxy formation history. The fraction of neutral hydrogen as a function of cosmic history allows for the measurement of the formation time for the first stars and quasar black holes in the early Universe. When the first luminous sources of light turn on, the IGM will be visible first in absorption and then in emission as these sources heat their surroundings.

Measurements of fluctuations across the sky will trace the growth of structure, testing cosmological models and allowing for the determination of how the heating occurs. Eventually, protogalaxies will ionize surrounding gas, turning off 21-cm emission. The pattern of ionized and neutral gas, and its time

evolution, will reveal the sources responsible for reionization. Canadians lead experiments looking for neutral hydrogen at high redshift (e.g., Paciga et al. 2013, MNRAS **433**, 629) and will pursue this topic with the SKA1-Low. High-resolution spectra of high-redshift radio sources will yield information about the early evolution of the cosmic web and the growth of ionized regions around protogalaxies.

The SKA-low opens up the potential of mapping the early heating epoch at  $z \sim 15$  (Alvarez et al. 2010, ApJ **723**, 17). The pre-reionization structures are a potential vast source of data for gravitational lensing, primordial gravitational waves (Masui et al. 2017, arXiv:1702.06552), non-Gaussianity, and much more. Almost all cosmological information in the universe is encoded in the period when the intergalactic medium spin temperature becomes coupled to the sub-microwave background thermal temperature by Lyman alpha pumping from the first stars. Canada is a world leader in this initiative.

With SKA1-low capabilities, we may image cosmic dawn (the first luminous objects in the universe) and, with SKA capabilities we may see beyond this epoch to the dark ages, before the first stars, when light from neutral hydrogen allows us to measure the power spectrum of structures in the very early universe. Canadians are leaders in this science and associated analysis techniques.