Astrophysical Masers:
Unlocking the Mysteries of the Universe
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Maser science with the Square Kilometre Array

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Abstract. The Square Kilometre Array (SKA), reaching a collecting area of one square kilometre, will be the world's largest radio telescope. Even in its first stage of deployment (SKA1, whose construction will be completed in 2026) it will enable transformational science on a very broad range of scientific objectives. Amongst them, there is the investigation of several Galactic and extra-galactic Masers. In this paper I will present the status of the SKA project and I will describe the capabilities of the SKA, with a focus on those that are more relevant for Maser science.

Keywords. intrumentation: interferometers, techniques: spectroscopic, physical and data processes: masers, Galaxy: kinematics and dynamics, radio lines: galaxies

1. The SKA concept

The SKA concept has been developed in order to answer to a set of fundamental questions:

- *The Cradle of life and Astrobiology:* How do planets form? Are we alone?
- *Strong-field Tests of Gravity with Pulsars and Black Holes:* Was Einstein right with General Relativity?
- *The Origin and Evolution of Cosmic Magnetism:* What is the role of magnetism in galaxy evolution and the structure of the cosmic web?
- *Galaxy Evolution probed by Neutral Hydrogen:* How do normal galaxies form and grow?
- *The Transient radio Sky:* What are Fast Radio Bursts? What haven't we discovered?
- *Galaxy Evolution probed in the radio Continuum:* What is the star-formation history of normal galaxies?
- *Cosmology and Dark Energy:* What are dark matter and dark energy? What is the large-scale structure of the Universe?
- *Cosmic Dawn and the Epoch of Reionization:* How and when did the first stars and galaxies form?

Such a broad range of science can be explored only by a very broad frequency range, which is probed by two separate instruments: the Low-frequency Array (SKA Low), from 50 to 350 MHz, as a single band, and the Mid-frequency array (SKA Mid), from 350 MHz to 24 GHz, as 5 bands, as detailed in Table 1. The former will consist of stations of log-periodic antennas and will be built in Australia; the latter will be an array of dishes built in South Africa. Both those sites have been selected as having very low Radio Frequency Interference (RFI), a feature that will be preserved in the decades to come, thanks to suitable agreements with the local governments. They already host radio astronomical facilities, including the SKA precursors MWA (Murchison Widefield Array, http://www.mwatelescope.org), ASKAP (Australian SKA Precursor,

Table 1. SKA frequency bands

Telescope name	Band name	Frequency range	Bandwidth	Notes
SKA Low	SKA Low	50–350 MHz	300 MHz	(1)
SKA Mid	Band 1	0.35–1.05 GHz	1 GHz	(1)
	Band 2	0.95–1.76 GHz	1 GHz	(1)
	Band 3	1.65–3.05 GHz	1 GHz	(2)
	Band 4	2.80–5.18 GHz	2.5 GHz	(2)
	Band 5a	4.60–8.50 GHz	2×2.5 GHz	(1)
	Band 5b	8.30–15.3 GHz	2×2.5 GHz	(1)
	Band 5c	15–24 GHz	2×2.5 GHz	(2)
	Band A	1.6–5.2 GHz	2.5 GHz	(2)
	Band B	4.6–24 GHz	2×2.5 GHz	(2)

Notes:
[1] Part of the baseline design and deployed as a top priority
[2] Deployed as an upgrade path (to be confirmed)

https://www.atnf.csiro.au/projects/askap/index.html) and HERA (Hydrogen Epoch of Reionization Array, http://reionization.org/) in Australia, and MeerKat (http://www.ska.ac.za/gallery/meerkat/) in South Africa.

2. SKA project schedule

The deployment of the telescope has been staged in two phases. In the first phase (SKA phase 1, or SKA1) around 131,000 of the total 1 million elements of the Low Frequency Aperture Array, and around 200 (64 of which will be integrated from Meerkat) of the total 2500 dishes of the Mid Frequency Array will be deployed. On phase 2, the remaining elements of the Low and Mid arrays will be deployed, as well as new technology (Phased Array Feeds and Mid-Frequency Aperture Array concepts are currently being developed). The deployment of receivers for the 5 bands of SKA Mid has been prioritised according to the science objectives they enable, with Bands 1, 2 and 5a/5b being the top priorities (see notes in Table 1).

The design process of SKA1 is expected to be complete in mid/late 2018, with construction beginning in late 2019 and ending in 2026. Early operations will begin in 2026/27 and routine operations in 2028.

3. SKA performance

The SKA will have a very good coverage in the visibility plane already in its first phase of deployment. This will guarantee excellent image quality, as illustrated in Figure 1. Figure 2 nicely illustrates the progress in sensitivity to be achieved in the next decades from the current state-of-the-art (LOFAR, uGMRT, JVLA and ALMA) with the deployment of SKA1 first, and, finally, SKA2. The analysis of the first prototypes for the Mid dishes (shown in Figure 3) has shown a total surface error RMS $< 350\,\mu$m and a relative pointing error RMS < 1.3 arcsec, which would guarantee a good high-frequency performance. This opens up the opportunity of extending the frequency coverage of the SKA beyond 24 GHz, subject to the interest of the community and the availability of funds.

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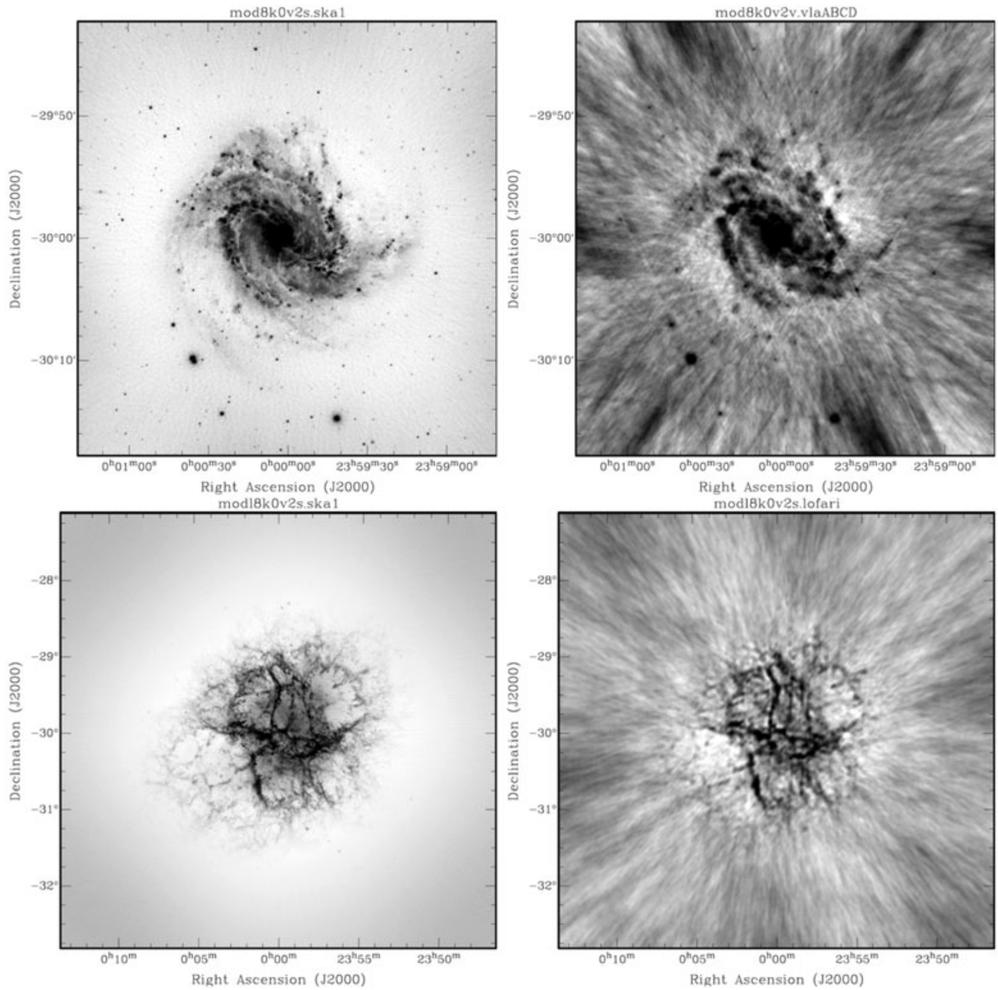

Figure 1. Image quality comparison between SKA phase 1 and the current state-of-the-art. *Top*: a single snapshot of SKA1-Mid (left) vs combination of snapshots in each of VLA A+B+C+D configurations (right). *Bottom*: a single snapshot of SKA1-Low (left) vs LOFAR-INTL (right).

4. SKA specifications for Maser observations

The relevant instrument for Maser science is SKA Mid, which will therefore be the focus of the next sections. In Table 2 we show some of the Maser lines that would be observable with the SKA. The design for the correlator of SKA1-Mid will be able to process frequency “slices” of 200 MHz with 65,536 channels, which corresponds to a channel width of 12.5 KHz. However, there will be also the possibility of “zoom windows”, where a smaller frequency range will be processed with the same number of channels, thus allowing “zooming-in” any relevant spectral feature, as detailed in Table 3. The frequency centre of zoom windows within an SKA band will be completely flexible.

The SKA will have VLBI capabilities for both Low and Mid. It will be possible to use either the whole array or a subset (subarray) of the SKA for VLBI purposes. The frequency centre and resolution of the VLBI observation will be set independently. High data rate recording and/or eVLBI interface will be used to make the data available for the VLBI analysis, outside of the SKA correlator.

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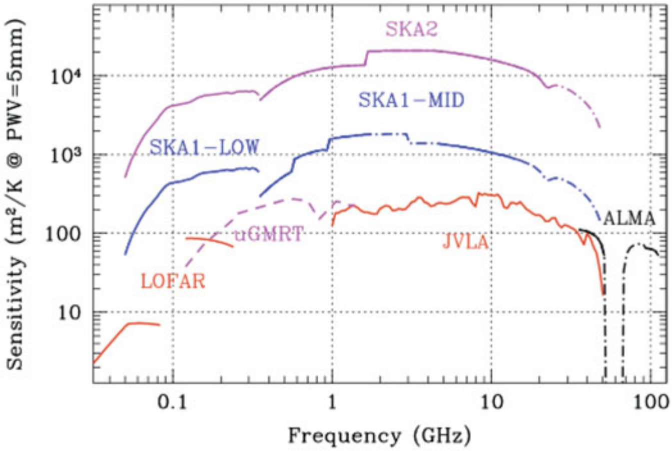

Figure 2. Sensitivity comparison between the SKA and the current state-of-the-art. The dot–dashed line on the SKA curves indicates frequency bands that are available as an upgrade path.

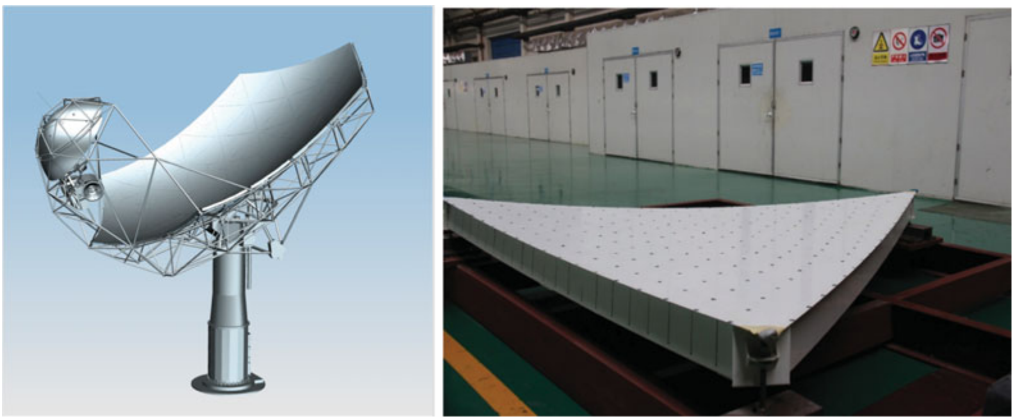

Figure 3. SKA-Mid dish prototyping. *Left*: model of the dish. *Right*: one of the panels, having an average surface accuracy of $\sim 250\,\mu m$ RMS.

5. SKA proposals

Two kinds of proposals will be invited for the SKA: "standard" PI-led proposals and Key Science Project (KSP) proposals. KSP proposals will typically require significantly more observing time and/or resources than PI-led proposals. As a general guideline, PI-led proposals would typically be observed within a single observing cycle while KSPs will typically run over multiple observing cycles. Time for both proposals will be allocated through normal submission and review procedures. The current working assumption is that between 50 and 75% of the time in the first five years of routine operations will be dedicated to KSPs.

One interesting feature that the SKA observations will have is the possibility of "commensality", which consists in multiple proposals potentially sharing the same data, with usage rights restricted to their science case. For example, a wide survey in continuum to investigate the star-formation history of the Universe could be used at the same time as a cosmological survey to investigate the large-scale-structures or to measure gravitational lensing. This will maximise the scientific output of the SKA telescope time and enable

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Table 2. Some of the Maser lines observable with the SKA

Molecule	Frequency [GHz]	SKA Band
OH	1.612	Band 2
	1.665	Band 2
	1.667	Band 2
	1.720	Band 2
OH*	4.750	Band 4
	6.030	Band 5
	6.035	Band 5
	13.44	Band 5
H_2CO	4.829	Band 4
CH_3OH	6.668	Band 5
	12.18	Band 5
H_2O	22.23	Band 5
NH_3	23.87	Band 5

Table 3. Spectral resolution with SKA-Mid *zoom windows*

Window [MHz]	200	100	50	25	12.5	6.25	3.125
Channel width [KHz]	12.5	6.25	3.12	1.56	0.78	0.38	0.19

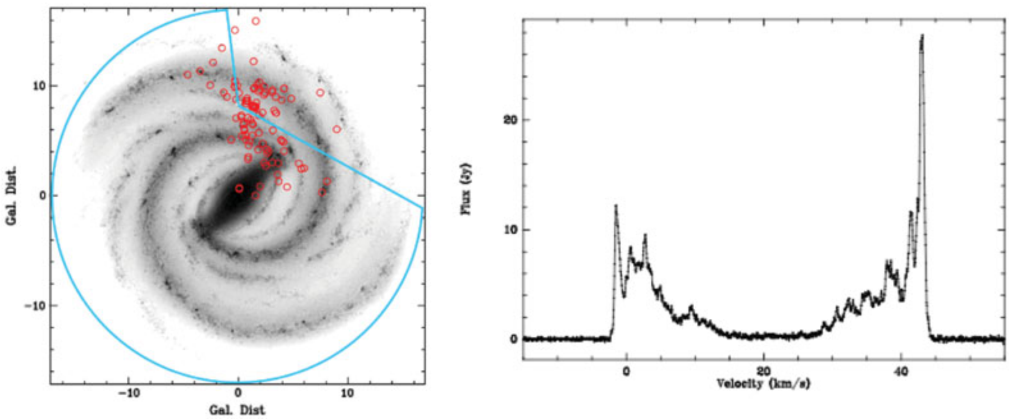

Figure 4. *Left*: Masers with astrometric parallaxes from the BeSSel survey and other observations (Reid *et al.* 2014) overlaid on the artist impression of the Milky Way, from Green *et al.* (2015). *Right*: 1612-MHz OH maser of the long-period variable star OH 16.1-0.2, from Etoka *et al.* (2015).

progressing with several KSPs simultaneously. The data will be also make completely public after a proprietary period, therefore constituting a legacy archive.

6. The SKA scientific community and Maser science

There is a large scientific community behind the SKA, who recently collaborated to produce an updated version of the science cases, published in the books *Advancing Astrophysics with the Square Kilometre Array*, available on `http://skatelescope.org/books/`. The community is organised in several science working groups, whose list is available on the SKA science website, `astronomers.skatelescope.org`. Participation to the working groups is open, and expressions of interest should be sent to the working group chairs, whose contact details are also provided in the SKA science website.

There is a huge potential in the SKA for doing Maser science, thanks to the the excellent sensitivity and image quality, good spectral resolution with flexible setup, VLBI

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capabilities and full polarization information. Some SKA Maser science cases are described in Green *et al.* (2015) and Etoka *et al.* (2015) (see also Figure 4). Moreover, the concept of commensality of SKA observations will allow using wide SKA surveys for blind Maser detection.

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