

The SKA and “High-Resolution” Science

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Abstract “High-resolution”, or “long-baseline”, science with the SKA and its precursors covers a broad range of topics in astrophysics. In several research areas, the coupling between improved brightness sensitivity of the SKA and a sub-arcsecond resolution would uncover truly unique avenues and opportunities for studying extreme states of matter, vicinity of compact relativistic objects, and complex processes in astrophysical plasmas. At the same time, long baselines would secure excellent positional and astrometric measurements with the SKA and critically enhance SKA image fidelity at all scales. The latter aspect may also have a substantial impact on the survey speed of the SKA, thus affecting several key science projects of the instrument.

1 Introduction

The benchmark design for the SKA Phase 1 [35], envisaging operations in the 0.3–10 GHz range and on baselines of up to several hundred kilometres, would have enabled addressing a range of scientific areas relying on sub-arcsecond resolution, including astrometry, pulsar proper motions, supernovae, astrophysical masers, nuclear regions of AGN, physics of relativistic and mildly relativistic outflows, kinetic feedback from AGN, evolution of supermassive black holes and their host galaxies [7]. The revised specifications for the SKA₁ [11, 14], shifting the operational frequency range to 0.07–3 GHz and limiting the baseline length to 100 km, leads to a reduction of the instrumental resolution to $0''.3$ – $1''.4$ for the dishes (in the 0.45–3 GHz range) and $1''$ – $8''$ for the aperture array (in the 0.07–0.45 GHz range).

The “stand alone” resolution of SKA₁ will therefore be sufficient for addressing only a subset of topics listed above. Achieving a higher resolution would rely on inclusion of external antennas and operating in the VLBI mode. This would be mostly

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feasible for the dish part of SKA₁, as most of the present day VLBI arrays are operating at frequencies above 600 MHz, and there are no definite plans to extend VLBI operations to below 300 MHz. SKA₁ operating in Australia can be an integral part of the LBA/NZ Network and EAVN. It would also have a somewhat limited common visibility with the VLBA. SKA₁ sited in South Africa will be a natural partner to EVN+ antennas. In both cases, collaboration with geodetic VLBI is possible, if 2.3 GHz will be maintained as a network frequency by the IVS.

In addition, the sub-arcsecond resolution of SKA₁ may actually be an essential requirement also for achieving the specifications envisaged for the traditional “low-resolution” science, including the surveying capabilities of the array (often viewed as a backbone of the instrument).

These two aspects of the relevance of long baselines to achieving the scientific goals of SKA₁ are discussed below, with Section 2 describing potential areas of broad scientific impact of high-resolution studies with SKA₁ and SKA Precursors and Section 3 discussing the effect of long baselines on the quality of imaging and surveying capability of SKA₁.

2 High-resolution science with SKA and SKA Precursors

With its present design specification, SKA₁ will be most effective addressing the following subset of topics mentioned above: studies of galactic and extragalactic supernova remnants, detection of atomic and molecular gas in galaxies, localisation of non-thermal continuum production sites in AGN, investigations of extragalactic outflows and their role in AGN feedback, studies of supermassive black holes and their relation to galaxy evolution, and research in AGN relic activity.

2.1 *Supernova science*

High-sensitivity radio observations at a sub-arcsecond resolution provide an effective tool to detect and monitor extragalactic SN/SNR [3, 25, 27], giving a good estimate of star-formation rate in target galaxies and helping assess the connection between AGN and star formation. These measurements rely on highly sensitive long baselines, and the improvements in sensitivity already enable detecting and imaging much weaker supernova remnants in the Milky Way as well [4, 29]. SKA₁ will enable detecting weaker SN/SNR in a much wider range of galaxies. The combination of high resolution and superb brightness sensitivity would enable much longer tracing of evolving supernova shells and supernova remnants, yielding essential information about their ages and galactic environment.

2.2 Atomic and molecular gas in galaxies

In addition to observations of line emission from H I (at 1.42 GHz) and D I (at 0.327 GHz), studies of OH megamasers (at 1.67 GHz) and H I/OH absorption made with SKA₁ will provide a wealth of information about atomic and molecular gas in the nuclear regions of galaxies [7, 22].

Extragalactic OH megamasers are detected towards IR luminous galaxies and they are 10^3 – 10^6 times stronger than brightest Galactic masers [16], and they are reported to have a two-component structure [17] possibly tracing an interaction between the ionisation cones of the nuclear outflow and the molecular torus. Combining SKA₁ with antennas on 3000+ km baselines would broaden spectacularly the scope of OH megamaser studies.

Absorption due to several species, most notably H I and OH toward compact continuum sources is a unique tool to probe nuclear regions on parsec scales – still beating the resolution and accuracy of optical integral field spectroscopy studies [31, 33]. In extragalactic objects, OH absorption has been used to probe the conditions in warm neutral gas [16], and CO and H I absorption has become a tool of choice to study the molecular tori [34] and interactions between outflows and ambient ISM [30, 33]. Studies of the nuclear absorption will benefit enormously from highly sensitive baselines provided by using SKA₁ alone or together with VLBI arrays.

2.3 Localisation of non-thermal continuum in AGN

Detailed knowledge of the mechanism of high-energy particle and emission production in AGN is pivotal for studies of galactic activity [24] as well as for understanding the kinetic and radiation feedback from AGN influencing cosmological galaxy evolution, black hole growth, and large-scale structure formation.

Self-consistent physical models for non-thermal continuum production in AGN require accurate information about the sites where the bulk of the high-energy emission is produced. Present arguments place these sites anywhere between ~ 1000 gravitational radii of the central black hole [1] and a ~ 100 pc separation from it [9]

Joint modelling of radio, optical, and X-ray data in 3C120 indicates that radio flares and X-ray dips seem to originate near the accretion disk [8, 26], while optical and high-energy flares are produced in stationary shocks located at ~ 1 pc downstream in the jet [2, 20, 36]. One important conclusion from this work is that instantaneous SEDs are likely to result from several physically different plasma components, which may lead to considerable difficulties in their interpretation being made without any reference to spatial location of the emission observed in different bands.

The combination of broad-band monitoring and high-resolution radio observations remains the only viable tool for spatial localisation of non-thermal continuum in AGN. Substantial improvements of sensitivity and time coverage of such combined programs can be achieved with SKA₁ working as part of VLBI experiments,

and it would be certainly provide essential information for understanding the physics of high-energy emission production in AGN.

2.4 Outflows and feedback in AGN

Evidence is abound for feedback from AGN to play an important role in physical processes at intergalactic and intracluster scales [5, 32], with the efficiency and mechanism of the kinetic feedback from nuclear outflows still being poorly understood.

SKA₁ will be an excellent tool for probing physical conditions in low-energy tail of outflowing plasma which is believed to carry the bulk of kinetic power of the outflow. This will enable making detailed quantitative studies of evolution and re-acceleration of non-thermal plasma in cosmic objects and provide essential clues for understanding the power and efficiency of the kinetic feedback from AGN and its effect on activity cycles in galaxies and cosmological growth of supermassive black holes. Such studies are critically needed for making a detailed assessment of the role played by AGN in the formation and evolution of the large-scale structure in the Universe.

2.5 Galactic mergers and supermassive black holes

High-resolution and high-sensitivity radio observations are expected to provide arguably the best AGN and SMBH census up to very high redshifts [7]. This will enable cosmological studies of SMBH growth, galaxy evolution, and the role played by galactic mergers in nuclear activity and SMBH evolution.

Most powerful AGN are produced by galactic/SMBH mergers [12, 15]. Activity is reduced when a loss cone is formed and most of nuclear gas is accreted onto SMBH [28]. The remaining secondary SMBH helps maintaining activity of the primary [13], and the evolution of nuclear activity can be connected to the dynamic evolution of binary SMBH in galactic centres [23]. Direct detections of secondary SMBH in post-merger galaxies are the best way to the evolution of black holes and galaxies together. Some of the secondary BH may be “disguised” as ULX objects [29] accreting at 10^{-5} of the Eddington rate. They are not detected in deep radio images at present.

SKA₁ would be a superb tool for detecting and classifying such objects, thus providing an essential observational information about the SMBH evolution in post-merger galaxies and its influence on the galactic activity, formation of collimated outflows and feedback from AGN.

2.6 *Radio relics and AGN cycles*

Nuclear activity in galaxies is believed to be episodic or intermittent, with estimates of activity cycles reaching up to 10^8 years [18, 38]. The episodes of activity are related closely to mergers of galaxies [37] and evolution of supermassive binary black holes resulting from galactic mergers [23, 28]. Both the onset and the latest stages of the jet activity are poorly studied at the moment, because in either case the flowing plasma emit largely at low frequencies.

Relics of previous cycles of nuclear activity are difficult to detect at centimetre wavelengths because of significant losses due to expansion and synchrotron emission. At centimetre wavelengths, such relics decay below the sensitivity limits of the present-day facilities within 10^4 – 10^5 years after the fuelling of extended lobes stops. This explains the relatively small number of such relics known so far. SKA₁, working below 1 GHz, would be able to detect such relics for at least 10^7 years after the fuelling stops, and this would make it possible to assess the activity cycles in a large number of objects, searching for signs of re-started activity in radio-loud objects and investigating “paleo” activity in presently radio-quiet objects. This information will be essential for constructing much more detailed models of evolution and nuclear activity of galaxies.

3 Long baselines for “low resolution” science

Availability of long baselines is not only a definitive requirement for a number of science areas relying on high-resolution imaging, but also an important factor for achieving design specifications envisaged for several key science areas of SKA₁ and full SKA. This concerns primarily the design goals for the survey speed and r.m.s. sensitivity to extended, low-surface emission.

3.1 *Imaging with the SKA*

In the SKA developments, imaging capability is often viewed as a “tradeoff” against the survey speed [10] – hence “core-spread” array configurations are favoured and long baselines are downgraded [11, 14]. But the two-order of magnitude sensitivity improvement envisaged for SKA will lead to situation when surveying is made in crowded fields with a number of resolved objects per primary beam of the receiving element.

In this circumstance, high fidelity imaging becomes then an essential feature rather than a “tradeoff”, and the combination $A_{\text{eff}}/T_{\text{sys}}$ becomes inadequate as a figure of merit describing the r.m.s. sensitivity and survey speed, $S_s \propto (A_{\text{eff}}/T_{\text{sys}})^2$.

It has therefore been argued [6, 21] that SKA needs to have the capability of imaging adequately (at least) all those spatial frequencies at which there is more than one sky object per primary beam.

3.2 Survey speed vs. imaging fidelity

Optimisation for the survey speed as expressed by the $A_{\text{eff}}/T_{\text{sys}}$ factor is based on two implicit assumptions:

- 1) The number of objects N_{source} detected in the primary beam area is small, $N_{\text{source}} \leq (B_{\text{max}}/D_{\text{ant}})^2$ (where D_{ant} is the diameter of antenna and B_{max} is the maximum baseline length);
- 2) All these objects are essentially unresolved by the array, implying that they have angular sizes $\theta_{\text{source}} \leq 2\text{FWHM}/\sqrt{\text{SNR}}$.

Neither of these two conditions will be realised in the case the case of both SKA and SKA₁. The primary beam area of a 12-m dish will contain ~ 50 objects ($S_{1.4\text{GHz}} > 0.4\text{ mJy}$) larger than θ_{source} . This leads to a strong requirement of optimisation for dynamic range and high-fidelity imaging (hence the distribution of the collecting area).

This effect has been investigated in a number of studies [6, 19, 21] showing that a uniform structural sensitivity is desired to alleviate the problems posed by resolved objects in the field of view. The structural sensitivity can be described by the uv -gap parameter [21], $\Delta u/u$. For an array uniformly sensitive to all detectable angular scales, $\Delta u/u = \text{const}$ on all baselines. The structural sensitivity of an array can be described by a factor

$$\eta_{uv} = \exp \left[\frac{\pi^2}{16 \ln 2} \frac{\Delta u}{u} \left(\frac{\Delta u}{u} + 2 \right) \right]^{-1},$$

with $\eta_{uv} \equiv 1$ for a filled aperture (for which $\Delta u/u \equiv 0$). An imperfect uv -coverage of an interferometric array results in an additional, scale-dependent factor of the image noise, $\sigma_{uv} = \sigma_{\text{rms}}/\eta_{uv}$, and this has to be taken into account when estimating the performance of SKA for surveys. These estimates should be done using the factor $\eta_{uv}(A_{\text{eff}}/T_{\text{sys}})$.

3.3 Configuration choices

Analysis based on the structural sensitivity factor shows that, compared to the ‘‘core-spread’’ array configuration (adopted as a benchmark for SKA₁ and SKA, a logarithmic [6, 21] or gaussian array of the same extent in baseline length will have an approximately 3 times worse brightness sensitivity on scales of $\leq 0.1 B_{\text{max}}$, a $\sim 30\%$

lower noise in snapshot images, and a ~ 2 times lower sidelobe level. For a 10 times larger gaussian/logarithmic array, these figures are reduced only slightly, while the confusion limit is lowered by a factor of 100. These arguments show that adopting such a configuration is rather a necessity for large area surveys. In contrast, for the core-spread configuration, the noise increase due to σ_{uv} would have to be offset by increasing the observing by a factor of 10(!) if one would require to reach within 5% of the r.m.s. specification based on the simple $A_{\text{eff}}/T_{\text{sys}}$ factor.

4 Conclusions

SKA₁ would be able to address a number of important astrophysical areas of study relying on high-resolution radio observations: studying supernovae; providing a good account of starburst activity in galaxies; using megamasers and nuclear absorption to probe the nuclear gas in galaxies; understanding in detail the physics of (ultra- and mildly-relativistic) outflows and their connection to the nuclear regions in galaxies; searching for radio emission from weaker AGN and secondary black holes in post-merger galaxies; and addressing the questions of relic activity and activity cycles in AGN. Reliable high resolution imaging is also needed for achieving the scientific goals in the key science areas of SKA₁ requiring low-resolution imaging and surveying of large areas in the sky, most notably the science areas considered as the very “selling point” of the instrument.

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