DOI: 10.18727/0722-6691/5362

ESO–SKAO Coordinated Surveys: the Galaxy

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Our Galaxy occupies a special place in astrophysics, because it allows us to observe fundamental phenomena at least four orders of magnitude fainter and at physical scales at least 100 times smaller than in any other comparable galaxy. Observations of the Milky Way therefore provide the fundamental data for our understanding of processes such as star and planet formation, the physics of accretion and ejection, interstellar chemistry or the interaction of the interstellar medium, stars and a massive black hole as it occurs in galaxy nuclei. In this article we discuss accretion and ejection in star formation, carbon chemistry, unidentified radio sources in the Milky Way, Galactic structure, and stellar remnants in the Galactic centre as exemplary science cases where multiwavelength observations with the SKAO and ESO facilities can make a profound impact. We also briefly discuss the nature of the coordinated observations and any requirements that we consider necessary to carry them out successfully.

Studying the accretion-ejection link in a young cluster deep field

The accretion and ejection of material are key processes that shape star and planet formation. Accretion impacts protostellar development and the pre-main-sequence phase, determining stellar masses and protoplanetary disc lifespans. The ejection of material (via outflows, winds and jets) influences the final stellar mass, the conditions in the planet-forming discs, and the wider star- and planet-forming environment. Despite this importance, our understanding of the link between accretion and ejection is limited. The upcoming joint operation of the SKAO and ESO facilities presents a unique opportunity to study the accretion-ejection link in unprecedented detail.

A proposed key science project for the SKAO involves observations of a nearby young stellar cluster to investigate many aspects of star and planet formation (see Hoare et al., 2015). The large field of view of SKA-Mid (between 6.7 and 60 arcminutes at 12.5–1.4 GHz) would enable contemporaneous 'one-shot' observations of many tens to hundreds of young stellar objects spanning a range of evolutionary stages in nearby star-forming regions (see Figure 1a). By performing repeated observations of these fields, it would be possible to i) build up deep observations, and ii) investigate temporal phenomena across the various epochs. The extremely sensitive observations will reveal both dust continuum and radio recombination lines throughout the star-forming region. Comparison of epoch-to-epoch data (with careful choice of cadence) will allow us to characterise any changes in the morphology and kinematics of thermal emission from protostellar jets and non-thermal emission from magnetic flaring activity, both of which are closely linked to accretion and ejection processes. An example of a radio jet observed in the transitional disc GM Aur using the

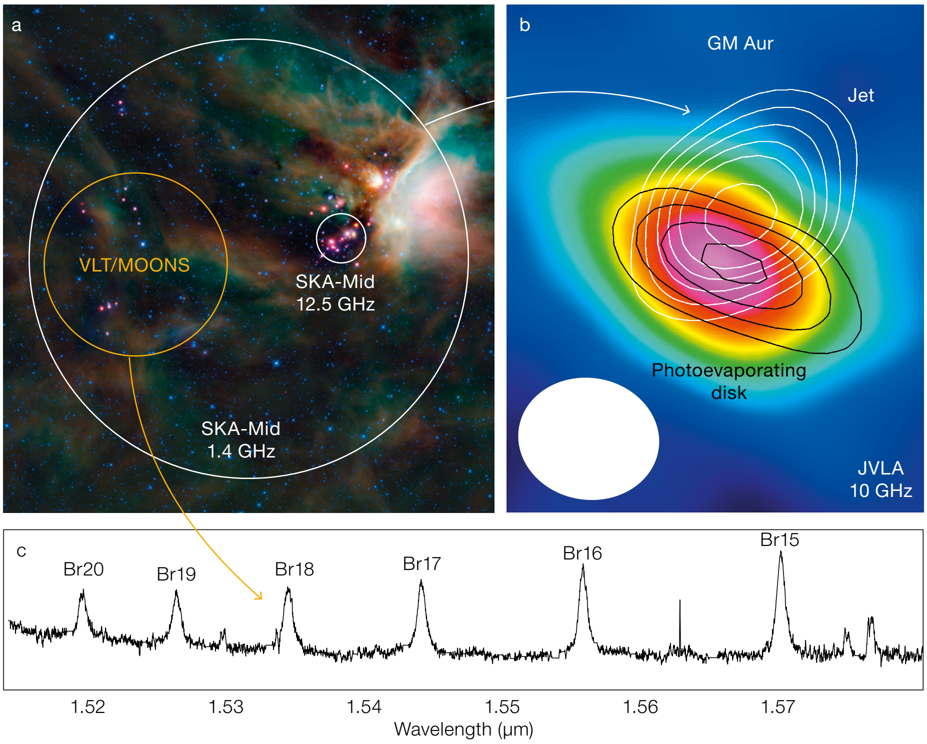

Figure 1. a) Comparison of the fields of view between MOONS/VLT and SKA-Mid between 1.4–12.5 GHz (Bands 2–5b) overlaid on a Wide-field Infrared Survey Explorer (WISE) image of ρ Oph (NASA/JPL-Caltech). b) JVLA observations of the photoevaporating disc and radio jet in GM Aur (10 GHz at ~ 0.5 arcseconds resolution; Macias et al., 2016). c) Brackett series of emission lines from a strongly accreting young stellar object identified in the Apache Point Observatory Galactic Evolution Experiment (APOGEE) survey (*H* band, *R* ~ 22 500; Campbell et al., 2023).

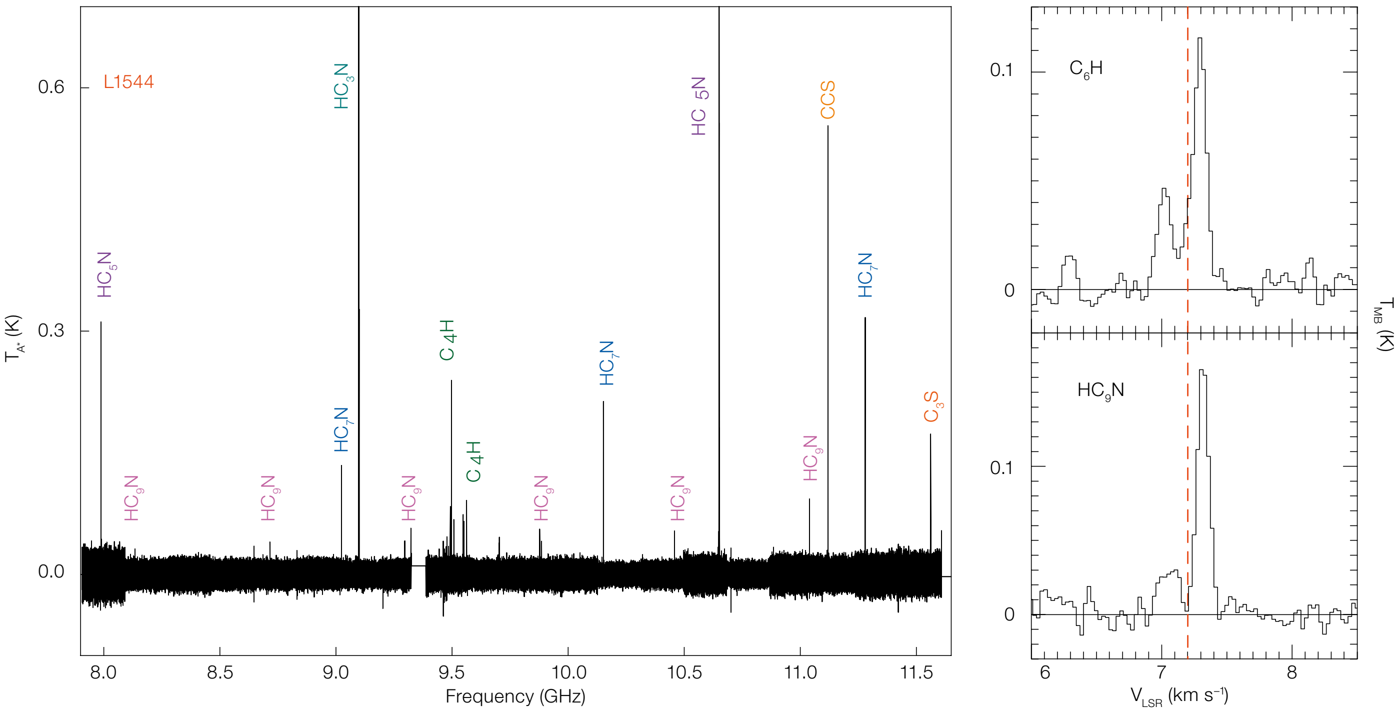

Figure 2. Complex carbon species observed towards the prestellar core L1544 using the GBT single-dish telescope (Bianchi et al., 2023). These observations have been acquired in the context of pilot projects aimed at preparing the scientific cases on C-bearing complex species observable in the frequency window of the SKA1-Mid Band 5.

Janksy Very Large Array (JVLA) is shown in Figure 1b (Macias et al., 2016). SKA-Mid will achieve an angular resolution more than 10 times smaller than these observations (0.034 arcseconds at 12.5 GHz). This, combined with sensitivities more than four or five times higher than what is currently possible, will enable a precise decomposition of the various processes occurring in young stellar objects that emit at these frequencies.

A natural synergy to this comes with ESO's Multi-Object Optical and Near-infrared Spectrograph (MOONS) instrument at the Very Large Telescope (VLT). MOONS will have the ability to simultaneously obtain one thousand multiplex spectra in the *H* band across a 25-arcminute field of view (see Figure 1a). This wavelength range (0.65–1.8 microns) covers a variety of diagnostic emission lines that can reveal much about the accretion processes in young stellar objects. Line luminosities can be converted to stellar mass accretion rates using well-calibrated scaling relations (for example, Fairlamb et al., 2017), spectrally resolved emission lines give clues to the morphology and kinematics (disc, jet, infall; for example, Chojnowski et al., 2017), and relative intensities can be used to derive physical conditions of the emitting material (for example, temperatures and densities, Campbell et al., 2023, and see Figure 1c).

SKA-Mid and MOONS/VLT will open a new window to understanding accretion and ejection in young stars. Owing to the highly variable nature of emission mechanisms in both the infrared and radio regimes (for example, Wolk et al., 2018; Curone et al., 2023), closely coordinated observations will be required (within days to hours). Such contemporaneous observations will reveal links between stellar accretion rates and outflow momentum rates, allowing us to understand the efficiency of star formation itself for the first time. The wide fields of view of both instruments will enable these studies to be performed on statistically significant numbers of young stars covering all evolutionary stages. For instance, the nearest star-forming region in ρ Oph contains many hundreds of Class 0–III YSOs (see Figure 1a). Combining these multiwavelength results will allow us to piece together the most detailed picture yet of how young stars and planets grow while interacting with their natal environment.

Complex carbon chemistry in Solar System analogues with the SKAO

Life on Earth is carbon-based, and carbon serves as the primary structural component, or 'backbone', of prebiotic species. Despite their crucial role in synthesising prebiotic compounds, complex carbon chains and rings (molecules containing more than five carbon atoms) remain relatively unexplored in astrochemical studies. This is primarily due to the faintness of spectral lines associated with complex carbon chains and rings at millimetre wavelengths, necessitating observations at radio wavelengths for their exploration.

Surveys conducted at radio frequencies using the Green Bank Telescope (GBT) and the Yebes 40-metre telescope have led to the detection of numerous complex carbon species in a few prestellar cores (McGuire et al., 2020; Cernicharo et al., 2021; Bianchi et al., 2023). These findings confirm the existence of complex carbon chemistry during the early stages of Solar System precursor formation (see Figure 1). If these species are stored within icy grain mantles and subsequently integrated into the disc, they will contribute to the organic material transported from the pre- and proto-stellar phases to newly formed planetary system objects such as asteroids and comets (Mumma & Charnley, 2011; Sakay & Yamamoto, 2013; Ceccarelli et al., 2023).

The unique synergy between SKAO and ESO facilities will provide us with the opportunity to explore, for the first time, the complete chemical composition of planet formation regions. On the one hand, the new Atacama Large Millimeter/submillimeter Array (ALMA) Band 1 and Band 2, along with the ALMA Wideband Sensitivity Upgrade (WSU), will allow us to study emissions from interstellar complex organic molecules. These molecules are species with more than six atoms, containing oxygen and/or nitrogen, and are considered the precursors of more complex prebiotic species. On the other hand, SKA-Mid will give us the unique possibility of exploring complex carbon species below 20 GHz in planet-forming discs.

The combination of the ALMA WSU and SKA-Mid will provide us with large spectral coverage, allowing us to have, for the first time, a complete view of the physics and chemistry of planet-forming discs, including the mid-plane region that is deeply obscured by dust opacity at high frequencies. Moreover, the large spectral coverage will ensure that we can observe several transitions and obtain the gas physical parameters via radiative transfer analysis or detect weak species via stacking techniques. We developed an SKA-Mid Scientific use case[1], in the framework of the Cradle Of Life working group, to observe the Orion molecular cloud 2 (OMC-2) region. This active star-forming filament hosts a diverse population of both low- and high-mass stars and discs (López-Sepulcre et al., 2013; Tobin et al., 2019), making it ideal for single-pointing observation within the large SKA field of view. Among these, the FIR 4 region is of particular interest because of its exposure to a flux of high-energy cosmic-ray-like particles (Fontani et al., 2017; Favre et al., 2018). This heightened exposure closely mirrors the conditions experienced by the young Solar System, which formed within a dense cluster of stars (Lichtenberg et al., 2019). Consequently, OMC-2 FIR4 is considered one of the closest analogues to the environment in which our Sun may have formed, making it an ideal location for studying chemistry reminiscent of our early Solar System. We propose to image the spatial distribution of complex carbon species in SKA-Mid Band 5 at angular scales of 0.5 arcseconds (corresponding to ~ 200 au at the source distance). This will perfectly complement surveys dedicated to the ongoing chemical exploration of the region at (sub-)millimetre wavelengths with ALMA and dedicated to the detection of interstellar complex organic molecules (for example, the ORion ALMA New GEneration Survey [ORANGES]; Bouvier et al., 2022).

Blind surveys of the Galactic plane and Galactic structure

Large-scale surveys of the Galactic plane at radio wavelengths can be used to study a very broad range of astrophysical phenomena (for example, Beuther et al., 2016; Brunthaler et al., 2021; Goedhart et al., 2024). With observations of the radio continuum one can observe various stages during the life cycle of stars and their interaction with the interstellar medium, from tell-tale tracers of star formation including compact, ultra- and hyper-compact HII regions, to radio continuum emission from active radio stars, to the graveyards of stars in the form of planetary nebulae and supernova remnants, as well as X-ray binaries and pulsars. Observations of polarised emission and spectral index information can be used to separate thermal from non-thermal emissions which will give important insights into the emission mechanisms of sources. On the other hand, observations of spectral lines give access to the gas in the Milky Way. Spectral-line observations give also access to kinematic information about the neutral atomic gas (for example, HI), the ionised gas (for example, radio recombination lines), and the molecular gas (for example, hydroxyl, methanol, formaldehyde).

Galactic plane surveys with SKA-Mid will deliver an unprecedented view of our Galaxy. Pushing sensitivity down to tens of microjansky, about 1000 point sources and 30 extended sources per square degree will be detected, enriching the census of Galactic objects and even allowing the discovery of new source types (for example, the ‘Odd Radio Circles’ described by Norris et al., 2021). In the Galactic plane, roughly a quarter of the point sources are likely Galactic (for example, Cavallaro et al., 2018). This result is usually derived from a statistical comparison with extragalactic fields and does not provide any useful information on single sources.

Radio spectral indices can help distinguish thermal and non-thermal sources, but degeneracy (when different kinds of sources share the same spectral index) and mimics (sources whose class has a typical spectral index may have a different one) strongly limit this method. In-band spectral indices are possible only for very bright sources and multi-epoch observations at different wavelengths are not capable of providing spectral information for variable sources.

In principle, cross-matching with optical and infrared surveys can provide a huge quantity of complementary data that can almost unambiguously classify a source. However, the mere positional cross-matching has proven unfeasible in many circumstances. On the one hand, at the typical resolution of current radio surveys (a few arcseconds, for example the South African Radio Astronomy Observatory’s MeerKAT Galactic Plane Survey), a single radio source may ‘cover’ several optical or near-infrared sources. On the other hand, surveys like the 2-Micron All Sky Survey are close to the confusion limit. Spurious matches are therefore very likely (for example, Umana et al., 2015).

The improvement in resolution and imaging fidelity (extended also to polarisation and time-domain) offered by SKA-Mid will certainly mitigate this problem. An SKA-Mid Band 5 survey of the Galactic plane, with a resolution better than 0.5 arcseconds, will represent a major step forward. This resolution is similar to that of the Visible and Infrared Survey Telescope (VISTA) and VLT Survey Telescope (VST).

After a first tentative classification, follow-up spectroscopic studies may be proposed in both the radio and optical/infrared. Both radio recombination lines and infrared lines can strongly constrain the nature of the source, supporting or discarding the cross-identification. Instruments like the Enhanced Resolution Imager and Spectrograph adaptive optics instrument at the Very Large Telescope (ERIS/VLT) will be perfectly suitable for near- and mid-infrared observations.

Depending on the nature of the source, simultaneous observations are usually not required. Variable sources (active stars, star-planet interaction) can instead benefit from simultaneity, even if, limiting to the simple classification, not strictly necessary. For certain science cases (such as luminous blue variable binaries), coordinated observations can be exploited to correlate the presence of infrared spectral features with the radio variability, further constraining the nature of the sources.

The interpretation of observations of Galactic sources depends critically on our knowledge of the distance to the object. Kinematic distances and luminosity distances can have very large systemic biases. Since many radio sources are located in the highly obscured spiral arms of the Milky Way, the Gaia space observatory is not able to see them and measure accurate parallaxes. However, radio waves are not affected by extinction, and using SKA-Mid in VLBI mode one can measure highly accurate parallaxes of radio continuum sources as well as maser sources in high-mass star-forming regions, which trace these spiral arms (Reid et al., 2019).

The Galactic centre

Embedded deep inside the Milky Way's bar, at 8.25 kpc from Earth, we can find the central components of the Milky Way: the four million solar mass black hole Sagittarius A* (Sgr A*), arguably the best studied object of its kind (GRAVITY Collaboration, 2020); the nuclear star cluster (~ 3 pc half-light radius and stellar mass ~ 2.5×10^7 $M_\odot$; Schödel et al., 2014); and the so-called nuclear stellar disc (vertical and radial scale heights ~ 30 and ~ 100 pc, respectively; stellar mass ~ 1.0×10^9 $M_\odot$; Launhardt, Zylka & Mezger, 2002). The Galactic centre (GC) thus contains the typical building blocks of a barred spiral galaxy. It is the only galactic nucleus that can be observationally resolved down to scales of milliparsecs (1 arcsecond corresponds to 40 milliparsecs at the distance of the GC).

On average, the GC is the most extreme astrophysical environment in the Milky Way. Its star formation rate, normalised by volume, is about two orders of magnitude greater than in the Galactic disc (Henshaw et al., 2023). The stellar density, the magnetic field and the properties of the interstellar medium in the GC make this region a nearby analogue to high-redshift star-forming regions (Kruijssen & Longmore, 2013). Because of its properties and nearness, the GC plays a unique role in astrophysics as a template for understanding the structure and kinematics of the stars and interstellar medium in a spiral galaxy nucleus and how those components interact with the massive central black hole. It is also an excellent proxy for the conditions in high-redshift star-forming galaxies.

As a result of this exceptional relevance, the GC has been extensively studied with all major observatories, such as the Atacama Large Millimeter/submillimeter Array (ALMA), the W. M. Keck Telescopes, the Hubble and James Webb space telescopes and ESO's VLT and VLT Interferometer. The high angular resolution and sensitivity of SKA-Mid, combined with its large field of view, will allow us to explore the radio emission from stellar and gas sources at the GC with unprecedented quality.

Much potential GC science with SKA-Mid does not necessarily require coordinated or quasi-simultaneous observations with ESO facilities. However, the study of neutron star and black-hole X-ray binaries (XBs) could receive a significant boost from a coordinated approach. The stellar density at the GC is extremely high, which may favour the dynamical formation of XBs (for example, Generozov et al., 2018). XBs have been reported to show a tight correlation between their radio and infrared luminosities when they undergo an outburst and enter the so-called hard state that is dominated by jet emission (see Russell et al., 2006 and Figure 3).

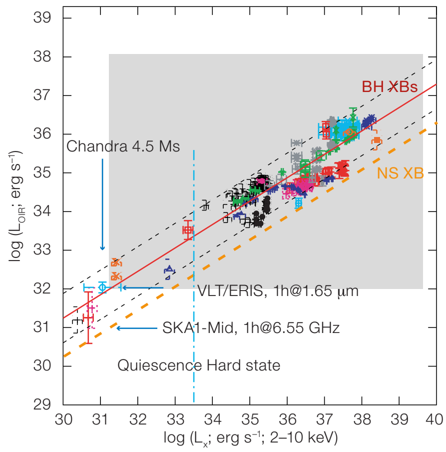

Figure 3. Radio–optical/infrared–X-ray correlation of XBs (Figure from Russell et al., 2006; different colours and symbols indicate different sources measured in different states). The flux densities are scaled to a distance of 8 kpc, closely corresponding to the distance of the GC. An extinction of 4.5 mag is applied to the near-infrared *H*-band fluxes. The continuous red line indicates the relation for black hole XBs and the dashed orange one for neutron star XBs. The blue, annotated arrows indicate, approximately, the detection limit of the 4.5 Ms deep Chandra field reported by Zhu, Li & Morris (2018), the one-sigma detection limit of SKA1-Mid imaging in one hour on source (using the SKAO sensitivity calculator[2]), and the detection limit of ERIS/VLT in the *H* band in a one-hour observation (several tens of sigma detection; the limiting factor is the stellar crowding in the GC).

This relation has been established only with a handful of sources at relatively uncertain distances. As shown in Figure 4, the GC can provide us with the opportunity to investigate these sources in large numbers and at a well-defined distance to constrain their radio–infrared correlation over more than six orders of magnitude in brightness. The observations will also serve to study their still poorly constrained recurrence times and to better understand the properties of the dark cusp of stellar black holes around Sgr A* (Hailey et al., 2018). Some pulsars/magnetars at the GC may also be detectable at infrared wavelengths, thus helping us to gain deeper insights into this population.

Based on our current knowledge of the star formation history in the nuclear star cluster (for example, Schödel et al., 2020), we estimate that the primary beam of SKA-Mid in Band 5b (central frequency 11.85 GHz) will contain ~ 10^5 neutron stars and a few times 10^4 stellar black holes when pointed at Sgr A* (Figure 2). If only

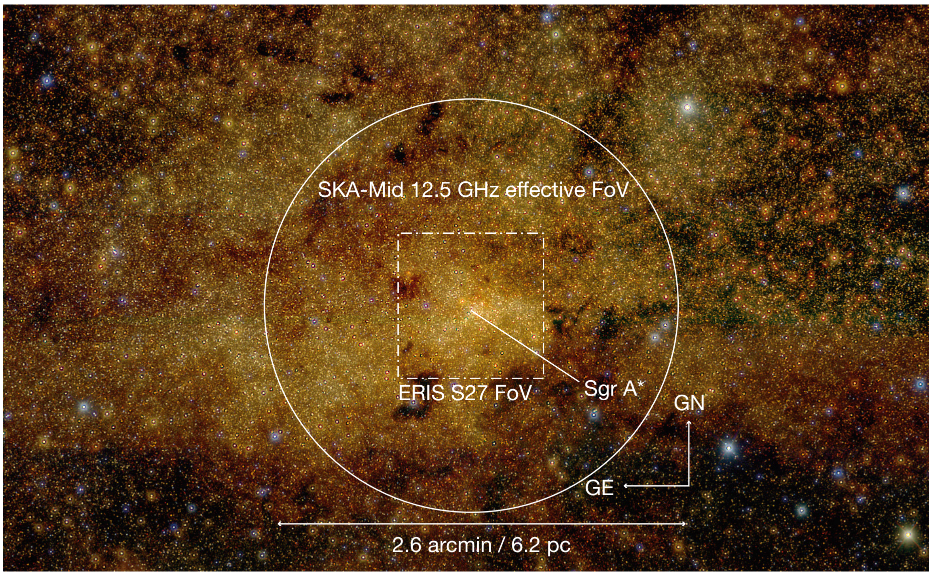

Figure 4. *JHK*s near-infrared image of the nuclear star cluster of the Milky Way. The circle indicates effective beam of SKA-Mid in Band 5a (central frequency 6.7 GHz). About 10^4 stellar black holes (and one supermassive black hole) and 10^5 neutron stars are located within this beam. The dashed square indicates the field of view of the near-infrared camera ERIS/VLT. The field of view of the future Multi-AO Imaging Camera for Deep Observations (MICADO) at ESO's Extremely Large Telescope will only be about 10% smaller.

a small fraction of them are contained in binaries, it is plausible that at any given time SKA-Mid will pick up an XB in a state bright enough that it may be detected by infrared imaging. The latter should be performed quasi-simultaneously with the radio imaging (within a few days). The angular resolution of SKA-Mid at band 5 (FWHM ~ 0.07 arcseconds) is an excellent match to that provided by ERIS/VLT. This high angular resolution is necessary to disentangle the crowded stellar field at the GC. The SKA-Mid observations can be used to trigger those by ERIS/VLT, which has a significantly smaller field of view. The GC contains a significant number of massive post-main-sequence stars (for example, Feldmeier-Krause et al., 2015) which will be picked up by the SKA1-Mid because of the thermal radio emission from their winds (for example, Yusef-Zadeh et al., 2015). These stars can therefore be used to cross-register radio and infrared imaging.

In order to reach down to almost quiescent black hole XBs and to constrain the recurrence time of these sources, repeated multi-epoch pointings towards Sgr A* over several years are required, with a total observing time of at least 100 hours per band. Quasi-simultaneous imaging with ERIS/VLT should be carried out in the *H*, and *K*s bands. One-hour observations, including overheads, will be sufficient. Two filters are required to confirm the location of the sources at the GC via their reddening. Observations in the *J* band would suffer from > 8 mag of extinction.

Owing to our limited knowledge about the target population (number of XBs, recurrence times, brightness range), it is currently hard to provide an estimate of the required time with ERIS. SKA observations should be followed up by infrared imaging within not more than a few days if changes are detected in the radio images. Only a fraction of the radio observations will require ERIS/VLT follow-up with a pointing towards the target of interest. If we assume that 30% of all SKA observations should be followed up, then an upper limit of 200 hours may be required with ERIS.

Summary

Combining observations using SKA-Mid in the radio regime with data in the millimetre, infrared and optical regimes is decisive for all the science cases described above. The multiwavelength data will allow us to identify reliably the types of observed objects and provide us with key information about the accretion/emission state of protostars and stellar remnants as well as about the interstellar medium. The necessary ESO facilities are primarily ALMA, VISTA, MOONS and ERIS on the VLT, and the VST. Quasi-simultaneous observations will be required for the young cluster field and stellar remnants at the Galactic centre, owing to the variability of the targets.

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Links

1. SKA scientific use cases: https://www.skao.int/sites/default/files/documents/d35-SKA-TEL-SKO-0000015-04_Science_UseCases-signed.pdf
2. https://www.skao.int/en/science-users/ska-tools/493/ska-sensitivity-calculators