Synergies of high-energy facilities with the SKA

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Abstract

The Square Kilometer Array (SKA) promises to revolutionise radio astronomy thanks to a significantly better sensitivity over the currently existing radio facilities. In parallel, the high-energy facilities that will be available during the early science and operations of SKA will also bring significant insight into the physics of non-thermal sources in the Universe. The combination of SKA with such high-energy facilities will allow a better understanding of the ongoing physical processes in the known sources and, hopefully, allow the discovery of new types of sources among a large fraction of still unidentified sources at high and very-high energy gamma-rays. Here we mention some of the high-energy facilities that will be available in the SKA era and comment on some physical cases where synergy between SKA and high-energy facilities could provide a significant impact.

1 Introduction

During the last two decades we have seen a strong development of X-ray astronomy thanks to X-ray satellites such as *RXTE*, *XMM-Newton* or *Chandra*, which provided timing, spectral and angular resolution capabilities, respectively. In the gamma-ray domain, old satellites like *CGRO* provided around two hundred of unidentified EGRET sources at High Energy (HE, $E > 100$ MeV) gamma-ray energies [20]. The orbiting *Fermi* satellite has already provided a few thousands of new sources and yielded the discovery of many new types of GeV sources [29]. At Very High Energy (VHE, $E > 100$ GeV) gamma-ray energies, Imaging Atmospheric Cherenkov Telescopes (IACTs) like H.E.S.S, MAGIC or VERITAS have already discovered more than one hundred TeV sources of different types [21][1].

Non-thermal sources in the Universe emit across the whole electromagnetic spectrum. Therefore, observations of these sources combining radio and high-energy facilities can help

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[1] See `http://tevcat.uchicago.edu/` for updates.

to better understand the ongoing physical processes. The superb sensitivity of the Square Kilometer Array (SKA), combined with existing and planned high-energy facilities, promises to revolutionise the study of non-thermal sources both in the Galaxy and beyond. This includes pulsars, binary systems of different types, supernova remnants (SNRs), active galactic nuclei (AGN) of different types, unidentified sources, etc.

In this chapter we mention high-energy facilities that could work together with SKA in Sect. 2, we comment on a few physical cases where the synergy between SKA and HE facilities could provide a significant impact in Sect. 3, and we make some concluding remarks in Sect. 4.

2 High-energy facilities in the SKA era

The early science phase of SKA should start in 2020. By that time, several X-ray and gamma-ray facilities covering the 0.1 keV to 100 TeV energy range should be available. Here we provide a non-exhaustive list of these high-energy facilities and their characteristics:

- X-ray facilities (see for example [27] and references therein). While some of the existing missions might be decommissioned before 2020, it is likely that *XMM-Newton* and *Chandra* will overlap the early science phase of SKA. These missions cover the ∼0.2–12 keV energy range and operate in pointing mode with a relatively small field of view (FoV) of $< 1^\circ$. The MAXI instrument onboard the *International Space Station* (*ISS*) provides an all sky monitor in the 1–20 keV band, and thus it is ideal for detecting new transient sources. The *INTEGRAL* and *NuSTAR* satellites operating above 10 keV and in the 10–80 keV energy range, respectively, are also likely to extend until 2020 and beyond, providing hard X-ray energy coverage for pointed observations. In 2015 the *Astro-H* mission, operating in the 0.3–600 keV range, should be launched, while *eROSITA*, to survey the whole sky in the 0.1–30 keV range, should be launched in 2016. Other future missions are *ASTROSAT*, with an all sky monitor similar to the one that was provided by *RXTE* (in 2015) or the *ISS* instruments NICER (in 2016), and the proposed LOBSTER with a very good all sky monitor. The chinese *HXMT* should operate between 2016 and 2020 with a huge FoV and sensitive between 20 and 200 keV. The *SVOM* mission, to follow GRBs but much more sensitive than *SWIFT*, is scheduled for launch in 2021. Planned missions include the X-ray timing *LOFT* mission in the 2–30 keV range (with a hard X-ray monitoring) recently proposed as an ESA mission for the M4 call and to be launched in 2025 if selected, and finally *Athena+*, due for launch in 2028 and with a superb sensitivity and spectral resolution in the 0.1–12 keV energy range. As can be seen, several X-ray satellites with different capabilities will allow detailed observations in the whole X-ray energy range during the early science of SKA and beyond.
- MeV facilities. The energy range between 1 and 100 MeV has been relatively poorly explored up to now, with old contributions by *CGRO*/COMPTEL and more recent ones by *INTEGRAL*. A proposal for an M4 mission to operate in the 0.3–100 MeV

energy range, namely *ASTROGAM*, has recently been submitted to ESA. The goal is to improve by at least one order of magnitude the sensitivity and by a factor of several the angular resolution of previous facilities. With a large 2.5 sr FoV, *ASTROGAM* promises a revolution at these low gamma-ray energies. If selected, it should be launched in 2025 and thus would provide a plethora of new sources to be followed at low energies with SKA during its operation.

- GeV facilities (see [13] and references therein). The *AGILE* and *Fermi* satellites are currently continuously scanning the sky in the ∼100 MeV to 300 GeV energy range. While *AGILE* will probably stop operations before the early science phase of SKA, *Fermi* will likely continue oparting through 2020 and potentially beyond, with both survey and pointed observations. In the future the *GAMMA-400* mission, planned for launch in 2021, will explore the sky in the 100 MeV up to 3000 GeV energy range in pointing mode, but reaching about an order of magnitude improvement in angular and energy resolution over *Fermi* at energies of 100 GeV. Therefore, detailed HE gamma-ray observations of known and newly identified sources should lead to a significant progress in our understanding of particle acceleration processes, which could be complemented with SKA ones already in the early science phase.

- TeV facilities. The IACTs H.E.S.S., MAGIC and VERITAS are currently operating above 50 GeV and up to several tens of TeV. With a limited energy resolution of ∼10% and angular resolution of $\sim 0.1^\circ$, they provide a FoV between 3 and 5°. More than a hundred sources of different classes have been discovered by these facilities, both in pointed and survey mode. The future in this energy range will be provided by the Cherenkov Telescope Array (CTA, [3]). CTA will have two arrays of Cherenkov telescopes, one in the north (either in Spain, Mexico or the USA) and a larger one in the south (either in Chile or Namibia) with a better access to the Galactic plane. CTA should operate from a few tens of GeV to above 100 TeV, improving the sensitivity by about an order of magnitude, and with enhanced angular and energy resolutions and larger FoV, over existing VHE gamma-ray observatories. The High Altitude Water Cherenkov (HAWC) will start full operations in 2015-2016, and will be used to perform a high-sensitivity synoptic survey of the sky at energies between 100 GeV and 100 TeV. At similar energies the LHAASO proposal is currently under consideration in China. All these facilities should discover more than a thousand new VHE sources during the early science phase of SKA, and should allow unprecedented studies of cosmic accelerators. Detailed studies of such sources with SKA will greatly help in modelling their multi-wavelength emission, thus allowing us to improve our physical understanding of them.

3 Possible major contributions of SKA to HE astrophysics

Pulsars

Pulsars have been traditionally discovered and studied at radio wavelengths. However, a number of pulsars have been discovered at X-rays and gamma-rays. In particular, the *Fermi* satellite has detected more than 117 pulsars at GeV energies [1]. Some of them do not have a radio counterpart. The Crab pulsar has also been detected with IACTs at sub-TeV energies [6, 30, 5], and it is expected that CTA will discover new gamma-ray pulsars [15]. Detecting the pulsed radio counterpart is important to understand the pulsar properties, but also because the dispersion measure of pulsars inferred with radio observations yields their (approximate) distance [12]. The distance to the pulsar is fundamental to scale its energy output at higher energies. Deep radio observations of pulsars discovered in X-ray or gamma-ray blind searches are also key for understanding the neutron star (NS) luminosity distribution.

Some pulsars display giant radio pulses (GRPs), with a sudden luminosity increase that can last microseconds, although they can show profile variability down to nanoseconds at radio wavelengths [19]. In the Crab pulsar, giant pulses have been also observed in the optical band [11], while searches have provided null results up to now at X-ray, GeV and TeV energies [9, 8, 7]. But do giant pulses occur at higher energies? If so, how does the energy output relate to the structure of the pulsar and its magnetic field? While SKA will be fundamental to understand the origin of GRPs, the possible high-energy counterpart will be searched and explored by fast and sensitive telescopes such as LOFT in X-rays and CTA at TeV energies.

Galactic binary systems

Accreting X-ray binaries have revealed a radio/X-ray correlation while in the so-called low-hard state, which is a fundamental tool to understand the behaviour and the different states of these sources. In the case of low-mass X-ray binary systems (LMXBs) the correlation has been densely explored for black hole (BH) systems even down to low luminosities [17], but this has not been the case for NS systems at low accretion rates ($L_{\rm X} \sim 10^{34} - 10^{36}$ erg s^{-1}). The slope of the NS-LMXBs radio/X-ray correlation seems to be different than the correlation for BH-LMXBs [23], but since the radio emission from NS systems is about two orders of magnitude fainter than for BH systems, that possibility has not yet been tested. Joint observations between SKA and the new generation of X-ray satellites are required to explore the correlation at very low accretion rates.

In the case of accreting high-mass X-ray binaries (HMXBs), Cygnus X-1 lies in the radio/X-ray correlation, but it always displays a very high X-ray luminosity. The recent discovery of the first HMXB containing a Be star and an accreting BH [10] has led to the X-ray detection of the first BH-HMXB in quiescence [25]. The source, namely MWC 656, remains undetected in radio [24], but its position in the radio/X-ray luminosity diagram may be consistent with the radio/X-ray correlation observed in BH-LMXBs. This suggests that this correlation might also be valid for BH-HMXBs with X-ray luminosities down to $10^{-8} L_{\rm Edd}$ [25]. Other quiescent BH-HMXB akin to MWC 656 could be discovered in the following years after performing extensive searches. Their detailed study to understand accretion at low luminosities will also benefit from combined observations between the SKA and sensitive X-ray satellites such as *Astro-H* or *Athena+*.

Interestingly, a different correlation has been recently proposed for the low-mass X-ray binary/MSP transition objects (tMSP) [14]. These systems, which have been observed to switch between radio millisecond pulsars and NS-LMXB, are a fundamental link between these two types of sources. They are also gamma-ray emitters that can show different states. Wide and deep surveys at radio wavelengths combined with high energy data will increase the number of such systems, which would help to understand the details of pulsar recycling models [28]. For instance, in X-rays the Wide Field Monitor (WFM) onboard LOFT, which will cover at least 50% of the sky simultaneously in the 2–50 keV energy band, will be a perfect discovery machine of X-ray transients.

On the other hand, gamma-ray binaries are high-mass systems that also display gamma-ray emission, in this case clearly detected up to TeV energies [16]. Their radio emission has been resolved at milliarc-sec scales [24], revealing cometary-tail like morpholgies that rotate with the orbital period. These systems are excellent but complex physical laboratories that need to be studied through the whole electromagnetic spectrum from radio to TeV energies. Since they are highly variable, joint simultaneous multiwavelength campaigns are required to understand them. Therefore, this type of systems will exploit the high-sensitivity, the fast response, and the flexibility of the next generation of instruments, from radio with SKA to TeV energies with CTA [26].

SNR and the origin of high energy cosmic rays

The work of identifying two SNRs as Cosmic Rays (CRs)' accelerators was selected as the Breakthough of the Year 2013 by the magazine *Science*. SNR constitute an important population of Galactic sources that generate VHE gamma-rays, and have been confirmed to accelerate protons, the main component of cosmic rays, to very high energy by their shocks [2]. Multi-wavelength observations at radio wavelengths and HE/VHE gamma-rays are a powerful tool to probe the particle acceleration mechanism in SNRs.

Magnetic field amplification is needed to accelerate cosmic rays to VHEs in SNRs. This could happen in small scale density perturbations and filaments in SNRs. The study of this filamentary emission requires radio observations at high resolution to reduce the depolarization caused by small scale distortion of the magnetic field. The low-frequency synchrotron emission (< 2 GHz) tracks the MeV-GeV part of electrons spectrum. The SKA1-LOW, with a frequency range between 50 MHz to 350 MHz, provides an excellent opportunity to distinguish the spectrum features produced from protons or secondary electrons [31]. This low frequency radio emission is linked to the GeV energy particles, whereas the high energy TeV particles can be studied through the X-ray synchrotron spectrum features. In the coming golden era of multi-wavelength astronomy, sensitive gamma-ray, X-rays and low frequency radio observations will simultaneously trace the emission produced by GeV and TeV particles from SNRs, and thus contribute significantly to solve the CR's origin issue.

Particle acceleration in extragalactic jets (AGN)

Relativistic jets in AGNs are among the most powerful astrophysical objects. However, despite their ubiquity, we still lack a comprehensive understanding of their internal physics and energy budget, their composition, and how they are formed and collimated. Some of the main open questions will be addressed with the deep, all-sky surveys (both total and polarimetric flux) from SKA1. These questions (from [4]) include: a) why are jets produced efficiently only in some systems, and what is the relation between jet power and the properties of the black hole and accretion system? b) what influence do magnetic fields have on jet formation, collimation, and maintenance up to distances above 100 kpc? c) what is the actual plasma composition at different jet scales and how does it evolve down the jet? d) how does the particle acceleration mechanism make the jet an efficient emitter on scales exceeding the size of the host galaxy? and e) how does the feedback between the jet and the (inter-)galactic medium influence the evolution of galaxies and clusters, and how do AGN jets and their central black holes evolve on cosmological time scales up to $z \sim 10$?

In particular, SKA will provide insightful information related to the high energy processes in AGN jets that are also producing the high-energy emission, and therefore coordinated multiwavelength studies will be mandatory. For instance, observations with SKA1-MID in South Africa should be coordinated with VHE gamma-ray observations conducted with IACTs like H.E.S.S. or CTA-South, optical telescopes like SALT, and supported by X-ray and HE gamma-ray observations from satellites.

To understand how jet propagation depends on the jet power and the environment, we need to observe large samples of weak jets at subarcsecond resolution down to noise levels of 1μJy/beam with SKA1-MID [22]. In more powerful jets, we want to test if the X-ray emission along the jet can be explained by inverse Compton with the CMB, or by a separate synchrotron component. These questions will be definitely solved by deep observations with SKA2, because we need a resolution better than 0.05 arcsec, ideally in the 1–10 GHz frequency range, with rms noise levels of roughly 10 nJy/beam and extremely high dynamic range, imaging fidelity and polarization purity. In summary, high-quality radio observations combined with X-ray observations will reveal the underlying non-thermal particle distributions, which can be used to constrain the acceleration processes at work.

Unidentified gamma-ray sources

Overall, about 30% of *Fermi* sources lack a high-confidence low-frequency counterpart [29]. Also, about 20% of the sources detected by the new generation of IACTs remain unidentified or with no firm low-energy counterpart[2]. The main reason is the large uncertainty of the gamma-ray positions, and also the fact that faint gamma-ray sources are usually associated with low flux density radio sources, whose space density is larger and which often lack a radio or optical spectrum. Deep and multifrequency radio surveys are fundamental to identify gamma-ray sources. By the time SKA will be operational, *Fermi* shall have completed at least a 10-year survey. At the same time, CTA will be starting its operation, and a moderately shallow wide area survey should reveal a large number ($\sim$ 100) of week and/or transient sources to be identified through carefull studies conducted at other wavelengths such as radio. A similar situation should probably happen with the unidentified multi-TeV sources to be discovered by HAWC during the $\sim$ 5 years prior to SKA early science.

Observations of these gamma-ray sources in radio with SKA1-MID will provide detailed

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[2] See `http://tevcat.uchicago.edu/`

properties of possible radio counterparts thanks to its sensitivity, flexibility, and sub-arraying capability [18]. When faint gamma-ray sources are considered, pure positional coincidences are not significant enough for selecting counterparts and we need additional physical criteria to pinpoint the right object. The criteria can be the radio spectral index, variability, polarization, or compactness, requiring the high angular resolution of SKA1-MID. Thus, detailed studies with SKA can help to identify the counterparts of the large population of unidentified gamma-ray sources.

4 Concluding remarks

The superb sensitiviy of SKA, in combination with the use of high-energy facilities, should allow us to better study and constrain different physical processes in a veriety of interesting objects, from pulsars to SNR and black holes of all masses. In addition, the follow-up by SKA of unidentified HE and VHE gamma-ray sources discovered by *Fermi*, CTA or HAWC should allow us to pinpoint the low-energy counterparts and potentially unveil new types of high-energy non-thermal sources in the Universe.

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