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The physics of the radio emission in the quiet side of the AGN population with the SKA

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Super massive black holes (SMBH) are thought to be ubiquitously hosted in massive galaxies. They may be either quiescent, like the case of Sgr A* in our Galaxy, or active, and they are at the basis of the phenomena known as Active Galactic Nuclei (AGN). In this case they often manifest their presence by releasing a huge amount of energy which usually overwhelms the star-related contribution of the entire host galaxy. Although they have been targets of many multiwavelength campaigns, the main physical processes at work in AGN are still under debate. In particular the origin of the radio emission and the mechanisms involved are among the open questions in astrophysics. The radio-loud AGN population and their radio emission is linked to the presence of bipolar outflows of relativistic jets. However, the large majority of the AGN population do not form powerful highly-relativistic jets on kpc scales, like those observed in radio galaxies and radio quasars. This does not mean that they are radio-silent objects. On the contrary, these systems are characterized by radio luminosity up to 10^{23} W/Hz at 1.4 GHz, challenging our knowledge on the physical processes at the basis of the radio emission in radio-quiet objects. The main mechanisms proposed so far are synchrotron radiation from mildly relativistic mini-jets, thermal cyclo-synchrotron emission by low-efficiency accretion flow (like ADAF or ADIOS), or thermal free-free emission from the X-ray heated corona or wind. The difficulty in understanding the main mechanism involved is related to the weakness of these objects, which precludes the study of non-local radio-quiet AGN. Multifrequency, high-sensitivity polarimetric radio observations are, thus, crucial to constrain the nature of the power engine, and they may help in distinguishing between the contribution from star formation and AGN activity. The advent of the Square Kilometer Array (SKA), with its sub-arcsecond resolution and unprecedented sensitivity will allow us to investigate these processes in radio-quiet AGN, even at high redshift for the first time. Both the broad-band radio spectrum and the polarization information will help us in disentangling between non-thermal and thermal origin of the radio emission. The jump in sensitivity of a few order of magnitudes at the (sub-)μJy level will enable us to detect radio emission from a large number of radio-quiet AGN at high redshift, providing a fundamental step in our understanding of their cosmological evolution.

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1. Introduction

Galaxies represent the majority of the observable matter in the Universe. Gravitationally bound gas, dust and stars are their basic constituents. In their centre a super massive black hole (SMBH) is usually found, and if it is in an "active" phase it is responsible for a significant contribution to the SED that cannot be attributed to other origins such as stars, gas and dust. In this case, the central region of the galaxy is termed an Active Galactic Nucleus (AGN) and is one of the most energetic phenomena in the Universe. Its emission is observed in a large range of the electromagnetic spectrum, from infrared (IR) to X-rays, by processes directly and indirectly related to the release of gravitational energy from matter falling onto the SMBH.
If the AGN is able to form a bipolar outflow of relativistic plasma, then its radio emission becomes comparable to or even stronger than the emission observed in the other energy bands. The presence, or lack, of relativistic jets is at the basis of the radio-loud and radio-quiet dichotomy. Only 10 per cent of the AGN population is radio-loud, while in the large majority the radio emission is a negligible part of the bolometric luminosity. The latter are termed radio-quiet AGN and their radio luminosity at 1.4 GHz does not exceed 10^{23} W/Hz (e.g. Condon et al. 1992).
Although the radio emission is a very marginal part of the energy released by radio-quiet AGN, it represents a unique way to investigate the high energy particle accelerators. Understanding the origin of the radio emission from radio-quiet AGN is not trivial. Usually radio-quiet AGN are hosted in late-type galaxies where star formation is responsible for the majority of the radio emission. For this reason, disentangling the AGN-related emission from the stellar contribution is a hard task to perform. The knowledge of the physical processes occurring in the nuclear region of radio-quiet AGN is a critical point for understanding differences and similarities with the radio-loud AGN population, as well as for investigating a possible link between the AGN and the star formation.
The advent of the Square Kilometer Array (SKA) will provide a jump forward in the observational capabilities reaching unexplored sensitivity levels, and thus allowing the study of faint and non-local objects, improving the statistics and providing a fundamental step forward in our understanding of the physical processes at work and their implications for the AGN feedback.
In this Chapter we briefly introduce the key issues about the radio emission in the radio-quiet AGN population and we discuss how the advent of the SKA will help in shedding a light on this hot topic. The Chapter is organized as follows: in Section 2 we present the state of the art of the radio emission in radio-quiet AGN; in Section 3 we indicate how SKA may address some open questions during the SKA1 phase, and the jump that is expected when the array will be fully operative. Concluding remarks are in Section 4.

2. Radio emission in radio-quiet AGN: state-of-the-art

2.1 The stellar contribution

A significant fraction of the radio emission in radio-quiet AGN comes from processes related to the stellar evolution, like synchrotron emitting cosmic rays accelerated by supernovae, and ther-

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mal free-free radiation from the ionized gas in star forming regions. The fact that the tight radio/far-infrared (FIR) correlation found for star-forming galaxies (SFG) holds in radio-quiet AGN supports the idea that the bulk of the radio emission in radio-quiet AGN is related to stellar processes, while the agreement is poor in radio-loud AGN due to the presence of relativistic jets (e.g. Padovani et al. 2011).
When observed with adequate angular resolution and sensitivity the radio emission is often spread across the host galaxy. A clear example is represented by the Seyfert galaxy NGC 1097. On arc-second scale the radio emission traces the profile of the host galaxy and its spiral arms (Hummel et al. 1987, Condon 1987), while on smaller scale the radio emission is organized in a spectacular circumnuclear starburst ring where several star forming regions are clearly identified.
Circumnuclear starburst emission enshrouding the central AGN is observed in many Seyfert galaxies, like Circinus (Elmouttie et al. 1998), NGC 7469 and NGC 7586 (e.g. Orienti & Prieto 2010). The co-spatial distribution of the AGN and starburst activity has suggested a connection between these two phenomena. A close link between star formation and radio emission in radio-quiet AGN is further supported by their evolution which is indistinguishable from that observed in SFG and their luminosity function (LF), which appears to be an extension of the SFG LF (Padovani et al. 2011).

2.2 The particle accelerators in the nuclei of radio-quiet AGN

The origin of the radio emission from the nucleus of radio-quiet AGN is a matter of debate. The fact that the FIR flux better correlates with the low-resolution kpc-scale radio flux density, rather than the high-resolution pc-scale emission disfavours a dominant stellar origin for the nuclear emission (Thean et al. 2000).
The main mechanisms proposed include 1) thermal emission/absorption from hot gas (Gallimore et al. 2004); 2) low-efficiency accretion/radiation flow (Narayan & Yi 1994, Blandford & Begelman 1999); 3) non-thermal synchrotron radiation from a mildly relativistic jet (Orienti & Prieto 2010), or 4) a combination of processes (Falcke & Markoff 2000, Ghisellini et al. 2004).
The study of a sample of local Seyfert nuclei pointed out an empirical correlation between radio and X-ray luminosities, suggesting that the accretion flow and the radio emission are strongly coupled (Panessa et al. 2007). Interestingly, this correlation seems the same as the one found for radio-loud radio galaxies, whose radio emission is related to relativistic jets. This may indicate a possible common mechanism between the two populations. However, this claim cannot be unambiguously proved due to the large difference in luminosity between Seyferts and radio galaxies.
Support for the presence of synchrotron emission from the Seyfert nuclei comes from the detection of radio structures similar to those observed in powerful radio source (i.e. jets, lobes and hot spots), like the case of Circinus (Elmouttie et al. 1998) and NGC 1068 (Ulvestad et al. 1987). In these two sources, evidence for AGN able to accelerate particles to high energy was claimed after the detection by the Large Area Telescope on board *Fermi* of γ-ray emission which seems to exceed the cosmic-ray contribution from the host galaxy (Hayashida et al. 2013, Lenain et al. 2010).
In Seyfert galaxies the radio emission is confined within the host galaxy, whereas radio galaxies have radio structures on scales up to hundred of kiloparsecs or even megaparsecs. Not all Seyfert nuclei behave in the same way. In particular, it has been found that flat-spectrum Seyfert nuclei

usually do not show extended morphology, and the radio emission comes from an unresolved (sub-)parsec-scale region (Anderson & Ulvestad 2005). On the contrary, in the steep-spectrum Seyfert nuclei the radio emission is not centrally concentrated, but rather is diffuse over a larger region (e.g. NGC 4151, Ulvestad et al. 1998). In some sources kpc-scale bubbles are observed (e.g. Mrk 6, Mingo et al. 2011). These bubbles may drive shocks in the interstellar medium of the host galaxy and may play a role in regulating the star formation in the hosts (e.g. Mingo et al. 2012). These differences may arise from different physical mechanisms: steep-spectrum nuclei may be able to produce extended, but slow jet structures, whereas in flat-spectrum nuclei the energy released by the AGN is mainly localized in the innermost region, without developing jets.

3. The role of SKA

Due to its weakness, the radio emission of radio-quiet AGN has been investigated mainly in nearby objects. If the resolution is not adequate, the nuclear component may be washed out by the stellar-related emission, and the radio properties may be contaminated by the contribution from different components.
VLBI observations have turned out to be an effective hunter of AGN by detecting compact, variable components with brightness temperatures above 10^6 K, and high core dominance (i.e. the ratio between the milliarcsecond and arcsecond flux density). Panessa & Giroletti (2013) studied a complete sample of local radio-quiet AGN by collecting heterogeneous VLBI observations, confirming the importance of deep high-resolution observations on more statistically complete samples and at different redshift. This issue becomes even more complicated when the sub-mJy population is taken into account due to observational limitations.
A correct determination of the stellar- and AGN-related emission is important for a comprehensive characterization of the radio emission from the AGN, its evolution and the possible interplay with the host galaxy. These key issues can be addressed by:

- determining the core dominance by comparing low-resolution and high-resolution radio observations, which provides information on the fraction of the radio emission concentrated in the central region,
- the study of the broad-band radio spectrum and the polarization properties of the nuclear region, which are important tools for testing whether the radio emission is synchrotron radiation.

The expected SKA performances will provide a jump forward in our understanding of the physics of these extraordinary celestial bodies.

3.1 Unveiling the nuclear emission with SKA1-MID

A primary requirement for the study of the AGN contribution to the radio emission is an adequate angular resolution. With a baseline of about 100 km, the SKA1-MID array has the potential to address this issue. The angular resolution that will be achieved ranges between ∼0.4 arcsec at

21 cm (band 2) and ∼0.07 arcsec at 3.6 cm (band 5). This resolution has already proved to be adequate for separating the AGN emission from the possible contribution of nuclear star forming regions. In fact, if we consider the bulk of the radio-quiet AGN at $z \sim 1.5 - 2$, a resolution of 0.07 arcsec corresponds to ∼0.6 kpc, while the host galaxy should have a total angular size of ∼2 arcsec. The separation of the nuclear emission becomes of course easier as we consider closer objects. In addition, a minimum baseline of ∼400 m will allow the detection of the diffuse emission in nearby objects up to ∼1.5 arcmin (band 2), enabling a proper spatial characterization of both star-forming processes and possible extended jet structures.

The availability of multifrequency polarimetric observations will be crucial for unveiling both the spectral index and polarization distribution. Assuming a continuum sensitivity (770-MHz band) of $\sim 0.57 \mu$Jy h$^{-1/2}$ (natural weight, Table 1 in Dewdney et al. 2013), it would be possible to study large sample of radio-quiet AGN with a 10σ sensitivity of ∼10 μJy (uniform weight) in a reasonable time. The high resolution coupled with the deep sensitivity will allow one to reliably separate the AGN emission from the stellar contribution. This would allow the study of radio emission from AGN with luminosity $L \sim 10^{18}$ W/Hz, $L \sim 10^{20}$ W/Hz, $L \sim 5 \times 10^{22}$ W/Hz, and $L \sim 10^{23}$W/Hz at redshift 0.01, 0.1, 1, and 2, respectively. The two-tiered survey at Band 5 will be a starting point for this study.

The availability of a (quasi-)continuous radio spectrum will be a crucial tool for addressing this issue. In fact, thermal and synchrotron self-absorbed spectra are expected to show different properties, like the slope and the location of the peak frequency.

Observations covering a continuous frequency range from ∼ 1 GHz to ∼ 10 GHz will be crucial for discriminating between the thermal and non-thermal radio emission. This would require that band 2 (950-1760 MHz), 4 (2800-5180 MHz) and 5 (4600-13800 MHz) should be installed in SKA1-MID. A flat spectrum up to high frequency will be a clear evidence for thermal emission, while a turnover around a few GHz strongly supports the non-thermal synchrotron radiation. Furthermore, if the peak of the spectrum is due to synchrotron self-absorption, the frequency is strongly related to the physical properties of the emitting region: $\nu_p \propto H^{1/5} B^{2/5}$, where H is the magnetic field and B is the brightness. If the magnetic field computed from the observational parameter is unrealistically high, then it would prove that the peak in the spectrum is not due to synchrotron self-absorption, like in the case of NGC 4457 where the estimated magnetic field was $\sim 10^9$ G (Bontempi et al. 2012).

A spectral resolution of 100 MHz would be adequate for a proper characterization of the radio spectrum. Assuming the performances expected for the SKA1-MID (∼63 and 82 μJy h$^{-1/2}$ for a 100 kHz spectral resolution in band 2 and 5, respectively), it would be possible to easily achieve a 5σ sensitivity of ∼20 μJy with a 100-MHz spectral resolution in about one hour (uniform weight). The broad-band radio spectrum may be combined with the polarization information for constraining the nature of the radio emission arising from different regions. For example, a jet structure is expected to show polarized steep-spectrum synchrotron emission, while the diffuse synchrotron emission from a star-forming region should be highly depolarized due to the tangled magnetic field caused by the supernovae explosions. However, low-resolution observations may cause beam depolarization in case of non-resolved jet structures.

A more complex issue will be understanding the physical processes at the basis of the nuclear, flat-spectrum emission from the core region. In principle one may expect that unpolarized emis-

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sion may originate in thermal bremsstrahlung radiation from the gas of the hot corona, while some (very low) level of polarization may be observed in presence of synchrotron self-absorption. However, we must keep in mind that strong depolarization from the gas enshrouding the central region is likely to play a major role. Therefore, the lack of polarized emission cannot reliably discriminate between the two processes.

The SKA1-MID early-science capabilities

Important results on local AGN would be already achievable during the early-science operations. Assuming a maximum baseline of $\sim$ 50 km, and the availability of frequencies up to 5 GHz (band 4), the resolution would be 0.2 arcsec. This would preclude us from resolving the central kiloparsec region beyond redshift $z \sim 0.4$. However, objects with $z < 0.1$ would be studied in excellent details and we should already be able to build the (quasi-)continuous spectrum of the different regions with a 5σ threshold of ≤ 60 μJy in a reasonable time. This would allow the study of objects with a luminosity of $L \sim 10^{21}$ W/Hz at redshift $z = 0.1$, down to luminosity $L \sim 10^{19}$ W/Hz at $z = 0.01$.

3.2 Towards the entire array: SKA

The advent of the full SKA array will provide a jump in the observational capabilities. The deployment of the receivers up to 24 GHz will provide a step forward in the study of the nuclear emission of either thermal or non-thermal origin. For a maximum baseline of 2000 km (i.e. 20 times longer than the SKA1-MID) the resolution at high frequency will be a few milliarcsecond, allowing the characterization of parsec-scale regions even at high redshift. This will be accompanied by an improvement of about one order of magnitude of the sensitivity, allowing the unprecedented detection of (sub-)μJy objects with largely affordable exposure time.
In addition to the study of the total intensity emission from the nuclear region, observations allowing the detection of circular polarization may be a fundamental tool for identifying cyclo-synchrotron emission from low-efficiency accretion/radiation flow.

4. Concluding remarks

The radio-quiet AGN population is expected to represent a large fraction of the faint radio sky that will be picked up by the Square Kilometer Array. Due to its weakness, the radio emission from these objects is not fully understood. Furthermore, the co-existence of both the AGN and star-formation activity makes the segregation of these two components a hard task. Constraining the radio properties of both contributions will be fundamental for determining the mechanisms at work, how they evolve, constraining the unbiased luminosity functions, and exploring a possible interplay between them.
The observational capabilities of SKA will be crucial for addressing these key issues:

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- disentangling the contribution of the star-formation activity from the nuclear emission in nearby as well as in high redshift objects. This will be achieved by the availability of high angular resolution and deep sensitivity,
- understanding the nature of the radio emission from the central AGN. The quasi-continuous radio spectra covering a large range of frequencies will help in discriminating thermal bremsstrahlung radiation from hot gas, from non-thermal synchrotron radiation,
- determining the presence of extended jet-like structure related to the AGN activity by the analysis of the polarized emission.

The advent of the Square Kilometer Array will provide a substantial advance in our understanding of the radio-quiet AGN population, and the role that they play in the evolution of the host galaxy.

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