Active galactic nuclei on parsec scales

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Abstract

The nuclei of active galaxies are the most powerful long-lived sources of radiation in the Universe. They often outshine the host galaxy in which they reside and are able to eject outflows or jets of relativistic plasma that emit all the way from radio waves to the highest energetic gamma rays. To understand the mechanisms that govern AGN we have to go down to parsec or sub-parsec scales, where a central engine formed by a supermassive black hole and a surrounding accretion disc produces helical magnetic fields in which jets are thought to originate. The exact role of the magnetic field and its structure, the composition and dynamics of the ejected jets, as well as the feedback effect of the jets on the gas and dust that surrounds the central engine are however still far from understood. The SKA, with its superb sensitivity and polarization capabilities, will allow for a relevant advance on the field of relativistic jets and in active galactic nuclei and their connexion with the fueling material and star formation present in the vicinity of the central supermassive black hole.

1 Introduction

More than six decades after the discovery of active galactic nuclei (AGN) by Carl Seyfert [49], these objects still represent one of the major puzzles in astrophysics. AGN are currently well known as the most luminous long-lived sources of radiation in the cosmos. They are powered by gas falling from an accretion disc onto a super-massive black hole (SMBH, $\sim 10^6$ to $\sim 10^9\,\mathrm{M}_\odot$) at the center of a large fraction of galaxies [32, 50]. Indeed, AGN are able to emit enormous amounts of rapidly variable radiation, within time scales from minutes to years, all along the electromagnetic spectrum (from the longer radio wavelengths to the most energetic TeV gamma-rays).

When considered at the smallest (parsec and sub-parsec) scales, AGN are ideal objects to further our understanding of relevant physical processes surrounding SMBHs. Among all AGN components, one of the most intriguing ones is the central engine. Relativistic jets in radio-loud AGN have not still revealed the detailed mechanism for their formation. In models of magnetically driven outflows (pioneered by Blandford-Payne [9], but see also [31]), the rotation of magnetic fields anchored at the base of the accretion disc generate a poloidal electromagnetic flux of energy (Poynting flux) that accelerates the magnetospheric plasma. Energy can also be extracted from rotating black holes with similar efficiencies by the Blandford-Znajek mechanism [10]. In general, it is thought that both mechanisms operate simultaneously to produce stratified jets in both composition and speed, with an electron-proton (slow) disc wind shrouding an inner electron-positron relativistic jet. The current paradigm of jet formation, and in particular the one for the jet composition and density stratification, its magnetic field intensity and configuration, as well as the one for the non-thermal particle distribution responsible for jet emission will be efficiently tested by future sensitive radio facilities as SKA, see Sections 2 and 3.

The existence of the dusty torus (a toroidal structure of dust and molecular gas that, depending on the viewing angle, obscures the inner AGN regions, in particular the broad line region) is the basis of the unified model for AGN [7]. Interferometric infrared (IR) observations show that the torus of Seyfert galaxies is rather small ($r \leq$10 pc at 12 μm, [12]), and therefore it cannot be directly imaged with current instrumentation. Thus, the only methods available to infer torus properties are IR interferometry, which is restricted to the most nearby and brightest AGN, and the fitting of nuclear spectral energy distributions (SEDs) with torus models. The peak of the torus emission in these models occurs in the mid-IR and the most realistic dust distribution is not homogeneous, but clumpy (e.g., [42]). Another important process that can be probed is the accretion of cold gas from kiloparsec to sub-parsec scales. While this gas is important for the accretion process that ultimately leads to relativistic jets, it can also be used to produce new stars. Both the basic geometrical properties of the dusty torus and those of the nuclear star formation regions will be accessible by SKA thanks to its unprecedented sensitivity and its good angular resolutions. How SKA will impact our current knowledge of these systems is outlined in Section 4.

The very large, several (hundreds of) kiloparsec-size, radio structures seen in radio galaxies are in general not observed in Seyfert galaxies and in many low luminosity AGN (LLAGN). In particular, large scale collimated jets are rare. However, collimated radio structures, at scales of parsec to hundreds of parsecs, appear to be common in LLAGN when observed with sufficient angular resolution and sensitivity [38, 41, 35]. These jets are the best laboratories to study galaxy-AGN feedback because of their frequent interaction with the innermost regions of the AGN [19, 52], see also the chapter by Perucho et al.

(this book). Typically associated with Seyfert/LINER optical spectra, LLAGN have typical radio luminosities from $\sim 10^{19}$ to $\sim 10^{21}$ W/Hz [40] and can be studied only in the Local Universe with current radio facilities. Systematic statistical studies including thousands of LLAGN up to the most distant Universe will be allowed by the SKA through both large area and deep surveys (see Section 5), which will help to solve the long-standing problem of the understanding of the ultimate reason for the radio-loudness of a fraction of the AGN population.

From the spectroscopic point of view, HI studies with SKA (Section 6) will provide unprecedented three-dimensional information of the gas distribution of the central regions of a large number of AGN, therefore allowing for reliable statistical studies over large populations. This will in turn allow for additional tests of the AGN paradigm, in particular on which regards to the properties of their tori.

2 The central engine

The basics of the central engine in radio-loud AGN have been outlined in Section 1. Two of the major challenges on the astrophysics of the inner regions of radio-loud AGN are the determination of the composition of the jet and the observational confirmation of the jet/disc-wind paradigm. If the jets are formed around the black-hole corona (Blandford-Znajek model, [10]), their composition should be dominated by electrons and positrons, whereas the load of particles from the accretion disc [9] would imply an electron-proton composition [51]. Full polarization observations (including circular polarization), using SKA-VLBI [44, 3, see also Chapter by Ros et al. (this book)] and the SKA alone [3], will allow to determine the jet composition (see [26] and references therein) and the presence or not of slower and denser winds originated at the accretion discs surrounding a jet fast spine. Furthermore, knowing the jet composition and the energy distribution of the particles is fundamental to measure the dynamical role of the magnetic field. SKA-MID on Band 5 using the SKA as a VLBI station will permit high-frequency observations of polarized light (4.6 - 13.8 GHz) that will help understanding the evolution of the magnetic field intensity along the jet, in the same line. Therefore, Blandford-Payne type models (where the jet is anchored to magnetized rotating discs and helical fields are generated in a natural way) should result in an edge-brightened polarization structure up to the base of the jet with a high degree of polarization. In contrast, Blandford-Znajek models, where the jet is driven by the SMBH spin, result in a more compact footprint of the jet, which implies a higher opacity and a smaller polarization degree. The observations will help to discriminate between the models and will therefore also represent an extra independent test of the jet formation mechanism that can add information relevant for studies of jet composition (see above).

The violent variability in many radio-loud AGN, in the form of high energy flares accompanied by the ejection of superluminal radio components (e.g., [33, 34, 1, 2]), implies strong non-stationarity of the central engine on time scales of one year. The theory governing this variability, most likely related to the change in the black hole magnetic field and accretion rate, and affecting the whole electromagnetic emission spectrum, has to be developed. In the currently accepted acceleration models by Vlahakis & Koenigl [55], jets change from Poynting

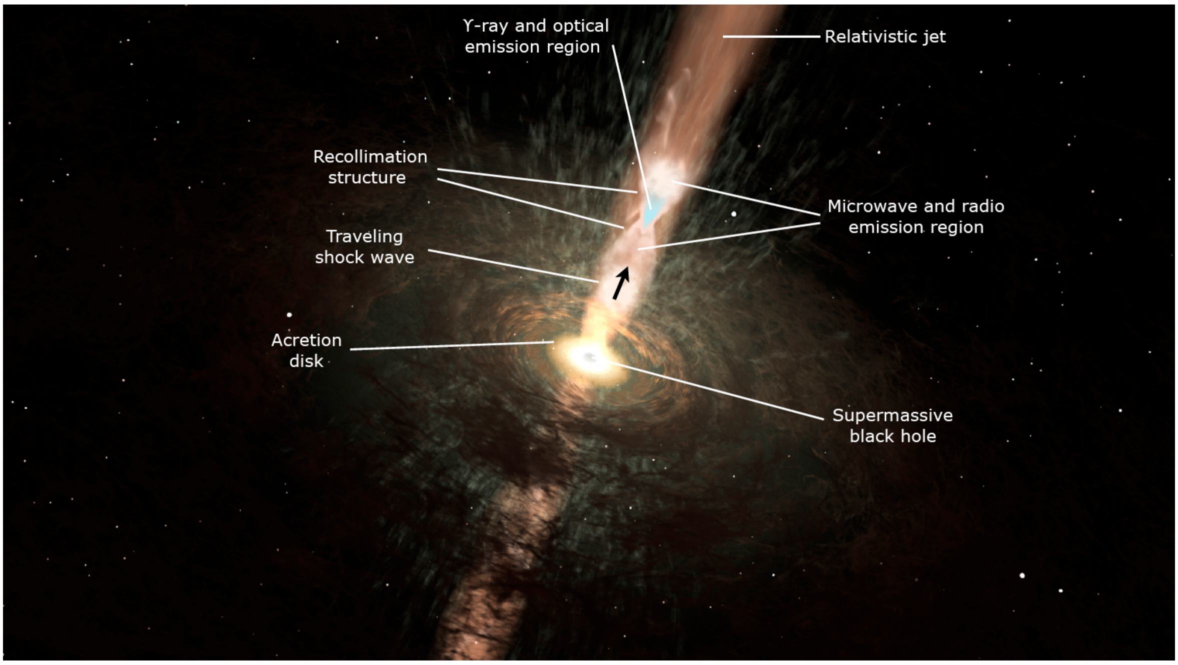

Figure 1: Conceptual representation of the multi-wavelength signature of the interaction of a moving shock with a stationary recollimation structure in the innermost regions of a radio-loud AGN, see [2] for an example of the observational basis of this model. Image credit: W. Steffen (UNAM).

dominated to particle dominated along the acceleration phase. One of the key parameters in these models is the initial magnetization of the wind, determining the asymptotic speed of the flow. It is expected that this relevant parameter for jet formation models can also be inferred from the previously outlined full-polarization observations with the SKA-MID and SKA-VLBI at the highest possible (range of) frequencies.

Another open issue is the division of AGN in radio-loud and radio-weak objects. Current observations seem to be more consistent with a smooth single distribution of radio loudness rather than a bimodal one. The superb sensitivity and survey speed of the SKA is expected to produce massive data sets of AGN in the entire domain of luminosities up to the nano-Jansky level, which will provide key answers regarding this long standing problem through the statistical study of unprecedentedly large samples [3].

3 Physics of jets and their magnetic fields

At parsec scales, several relevant open questions remain unanswered regarding the study of relativistic outflows from radio-loud AGN. These include the actual structure of the magnetic field, the jet composition, its possible transversal stratification, and the role of the magnetic field on the jet dynamics after the acceleration of the jet flow. This jet acceleration is thought to be produced by conversion of magnetic energy into kinetic energy of the particles (e.g. [55] and [29]). The unprecedented sensitivity of the SKA will allow to perform detailed studies of the interaction regions between traveling perturbations and standing shocks at the compact regions of jets within their radio-cores, which have been claimed to be the origin of multi-wavelength flares (see e.g., [34, 1, 16, 17], and Fig. 1) in blazars and radio galaxies that are observed at small viewing angles. In particular, SKA-VLBI at the highest possible observing frequencies will grant a detailed study of a number of jets in which these flares are produced and help determining the exact regions and processes by which they are produced. Polarization observations will also allow to determine the exact behavior of the magnetic field in this whole process and will help constraining the parameter space of these events, which can be related to the SMBH/accretion-disc system [33] and to the acceleration mechanisms that end up in the production of X-rays and gamma-rays from these sources.

The excellent sensitivity and polarization purity of the SKA (see the SKA1 Baseline Design and [3]), both on VLBI mode [44, see also Chapter by Ros et al. (this book)] (for non local radio-loud AGN) and with SKA-alone observations (for nearby AGN), will certainly impact our knowledge of the physical properties of the parsec scale region of extragalactic relativistic jets and their immediate environments. The SKA will allow, for the first time, to resolve a large number of parsec-scale jets on the transversal direction to their axis, and even to image the counter-jets in a fraction of them.

If the parsec-scale jet is threaded by a magnetic field with a helical structure, as expected from currently accepted jet formation models (see Section 2) and inferred from VLBI observations [8], detectable stratification in the total and linearly polarized emission is expected across the jet axis [30, 6]. This, together with Faraday rotation studies, would allow for a determination of the three dimensional structure of the magnetic field and flow velocity [21]. The case where both the jet and counter-jet can be observed is particularly interesting. In this case, measurements of the flux density ratio between the jet and counter-jet features, as well as their proper motions, provide a direct determination of the jet viewing angle and bulk flow velocity. These studies would require polarimetric multi-frequency SKA-VLBI observations at the highest possible frequencies, therefore achieving the necessary angular resolution to image the innermost regions of AGN jets.

Although there are indirect indications for the existence of a significant toroidal component in the parsec-scale magnetic fields of AGN jets [20, 8], only two direct cases (involving polarimetric imaging of the actual magnetic field) have been reported so far, see [56, 36] and Fig. 2. These latter two cases are still under debate though, because of unavoidable uncertainties on the actual nature of the source of polarimetric emission. Such definitive direct evidences require deep and transversely-resolved SKA-VLBI observations of the parsec-scale emission at a broad range of high frequencies from a statistically significant sample of jets. This will allow (with the help of detailed Faraday rotation images and profiles) to shed light on the actual magnetic field strength and its three dimensional structure, as well as on the low-energy particle properties.

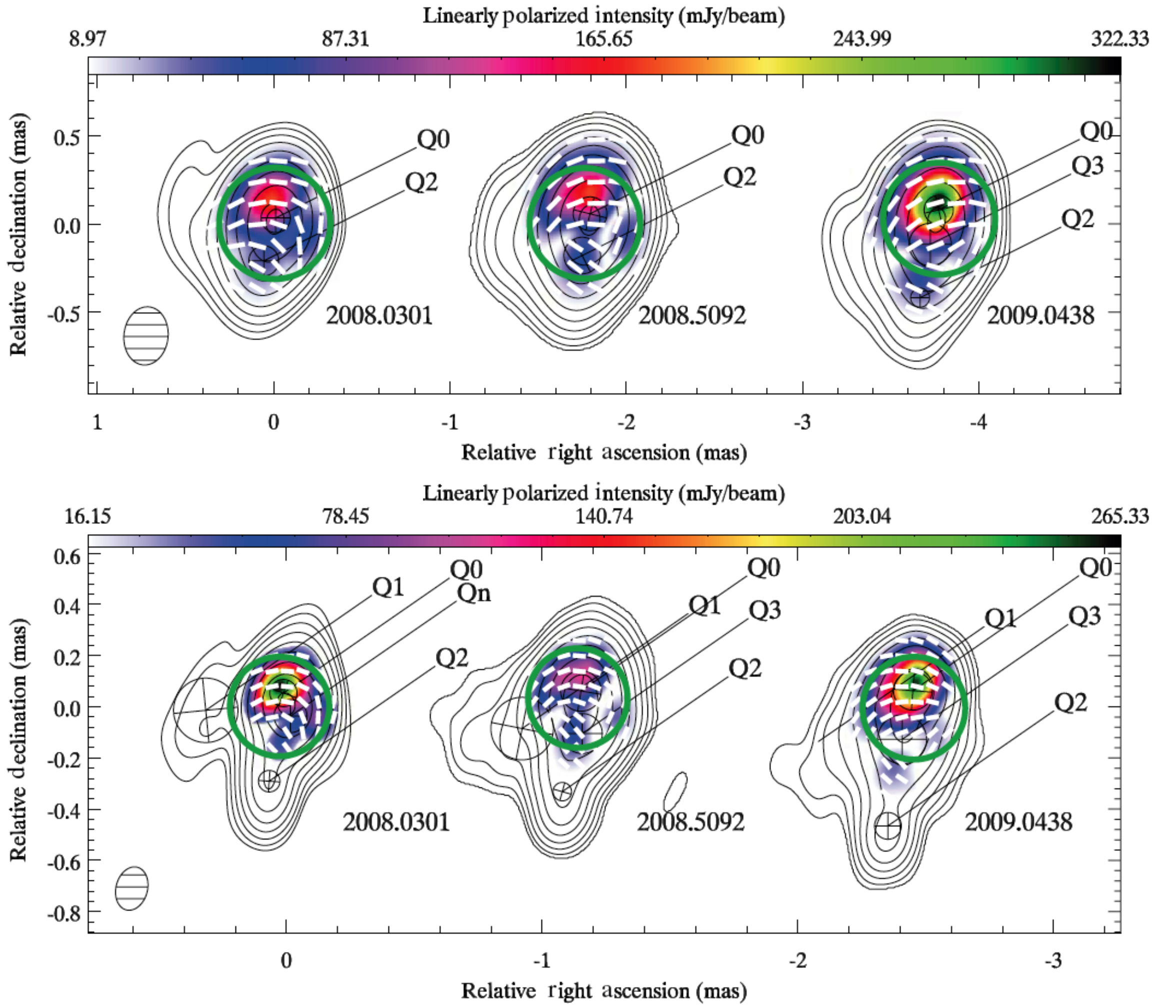

Figure 2: VLBA sequence of total intensity images (represented by contours), linearly polarized intensity images (represented by the color scale), and magnetic vector polarization angle distribution (symbolized by short white sticks), of the radio loud quasar NRAO150. The top three images were obtained at 22 GHz, whereas those on the bottom side correspond to 43 GHz observations. Assuming that the the observed structure corresponds to the strong radio jet on NRAO150 as seen face-on (i.e. pointing at $\sim 0°$ to the line of sight), the green line would represent the toroidal component of the magnetic field that would be observed in this case. The images show a good match with the observed magnetic vectors. Reproduced from [36].

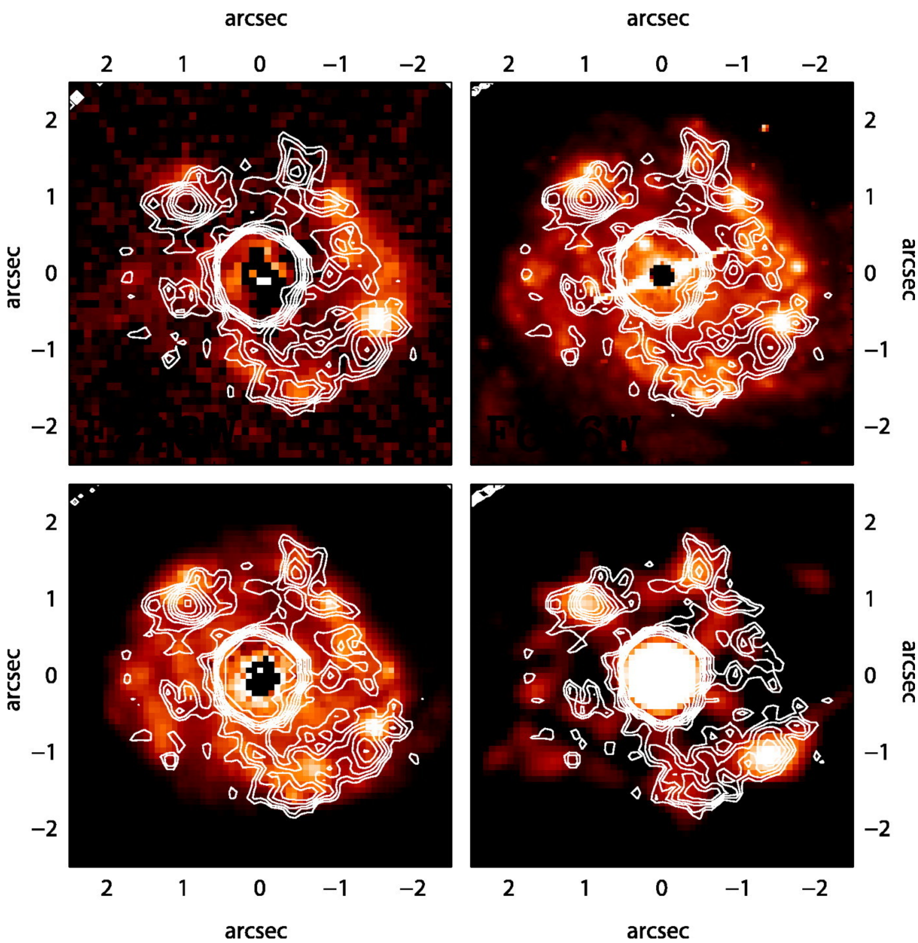

Figure 3: Multifrequency observations of the central region in NGC 7469, which contains a bright Seyfert 1 nucleus and a circumnuclear ring of star formation. Contours are the mid-IR 12.5 μm emission superimposed on the ultraviolet, optical, radio 8.4 GHz, and near-IR continuum maps (from top left clockwise). There is an excellent spatial correspondence between the extended mid-IR emission probing the on-going star formation activity in the ring and the radio continuum emission. Figure from [14].

4 The dusty torus and nuclear star formation

In the last few years we have started to constrain the torus properties of radio quiet AGN using sub-arcsecond resolution infrared (IR) data. These properties include, for example, the torus size, inclination, and covering factor [54, 46, 47, 4, 12]. However, those results are not statistically significant because the samples studied are not complete, due to the paucity of both interferometric and sub-arcsecond imaging and spectroscopic IR observations. Besides, the torus model parameters that describe the torus geometry and properties are highly degenerated. Therefore, to reduce these degeneracies it is paramount to have observational constraints on the torus properties such as its inclination angle. For a handful of galaxies, we can infer the torus inclination from the orientation of the ionization cones, but this is definitely not sufficient for a statistical study. High angular resolution and sensitive radio observations of nearby AGN have the potential to solve this problem. Parsec-scale jets have been detected in low and intermediate-luminosity radio-weak AGN [28, 48, 39, 35] and the orientation of these jets, together with other observations, can be used to constrain the torus inclination. In addition, radio observations of water and OH masers are unique tools for investigating the structure and kinematics of the gas in the immediate vicinity of the AGN central engine (e.g., [11]), and they can also provide constraints on the torus inclination angle.

The fueling of AGN requires the cold gas to be driven from the kiloparsec-scale host galaxy to physical scales of less than a parsec. As this cold gas is also the fuel to form new stars, nuclear star formation (on scales of less than 100 pc) appears to be an inevitable consequence of gas accretion processes. Moreover, numerical simulations predict that the star formation rate and black hole accretion rate should be tightly correlated on nuclear scales in AGN (see e.g., [27]). There is plenty of observational evidence for nuclear star formation in the inner $\sim$100 pc of nearby Seyferts using high angular resolution near and mid-IR observations [13, 53, 15, 5], as well as very long baseline interferometric (VLBI) radio observations [45]. However, star formation indicators such as ultra violet emission, hydrogen recombination lines, and polycyclic aromatic hydrocarbon emission are not straightforward to use in the nuclear regions of AGN, as they can be easily contaminated or diluted by the bright AGN emission and additionally obscured in type 2s. Radio continuum observations can be used to trace star formation activity in AGN as they are not affected by extinction, although observations at different frequencies are necessary to distinguish between thermal and non-thermal processes in the nuclear environment of galaxies (see [25] and references therein). Until a few years ago, sensitive radio observations could only trace star formation activity on kiloparsec-scales (see Fig. 3) in nearby Seyfert galaxies. However, recent high-angular resolution ($\lesssim$ 10 mas) radio observations with the high sensitive European VLBI Network has proven to be an excellent tool for scrutinizing the inner $\approx$ 100 pc region of local ultra luminous IR galaxies. For the case of galaxy Arp299-A (D= 45 Mpc), an extremely prolific supernova factory was discovered in the central 150 pc, together with a low luminosity AGN at a mere distance of 2 pc of a recently exploding core-collapse supernova [45]. More recently, it has been reported evidence for the existence of nuclear discs ($\lesssim$ 100 pc in size) in starburst galaxies from their radial distribution of supernovae [24].

The good angular resolution and superb sensitivity of the SKA will allow to determine the orientation of the parsec-scale jets as well as to characterize nuclear masers, when present, in complete samples of low and intermediate-luminosity radio-quiet AGN. These observations will be key to set constraints on the torus models and study the kinematics of the nuclear gas, and will include not only nearby AGN but also intermediate redshift radio-quiet AGN where such constraints are lacking. The large field of view of the SKA and its good angular resolution will also allow to characterize both the nuclear and circumnuclear star formation activity of large samples of radio-quiet AGN.

5 Low luminosity AGN

Most of the SMBH at the center of galaxies are thought to go through phases of activity during their evolution. However, the duty cycle of such phenomenon is currently not well constrained. The detection of compact jet emission in the low power counterpart of double size radio sources, Seyferts and LLAGN is a key test for the AGN unification scenarios. LLAGN are thought to be characterized by radiatively inefficient accretion (frequently modeled as advection-dominated accretion flows). They sometimes show small scale and low luminosity compact radio jets that can be useful to explain properties of the system, but observational parameters like intensity and polarized flux density, spectral index, size and variability are only available for a few very bright and nearby cases. Most AGN would not be radio silent at their radio quiescence phase. Therefore, radio observations will be paramount to detect LLAGN and probe the physics of their accretion flows. Their radio detection rate is relatively large, about 67% of LLAGN on the Palomar sample show extended jet emission at sub-arcsecond resolution, indicating that most LLAGN are energetic enough to power parsec-scale jets, see Fig. 4 and [45, 35]. The reason why their radio emission often appears compact is that previous radio observations were not sensitive enough or did not have enough angular resolution. The large collecting area, good angular resolution and contiguous frequency coverage of the SKA will allow to unveil these mini-jets, their morphology, and spectrum in full detail in representative samples of AGN covering a much wider range of luminosity and radio loudness than feasible before. SKA surveys will become an efficient tool to search for faint (intrinsically weak or not) AGN. Latter, SKA continuum observations in the 1 to 3 GHz range will be ideal to improve our current knowledge, since many more sources will be revealed, both fainter ones in the Local Universe, and with much more distant galaxies. Variability studies are currently limited by sensitivity, which will not be a major limitation in the SKA era. The comparison between the jet structure and the surrounding ionized gas at similar angular scales will allow a direct assessment on the jet power dumped into the medium (see for example the study in the X-rays by [22, 23]).

6 HI studies of AGN

One of the relevant observing opportunities with the SKA will be HI imaging of galaxies with unprecedented detail, see the chapter by Verdes-Montenegro et al. (this book). The SKA is an optimum instrument for measurements of the HI 21 cm line, in the region around 1.4 GHz

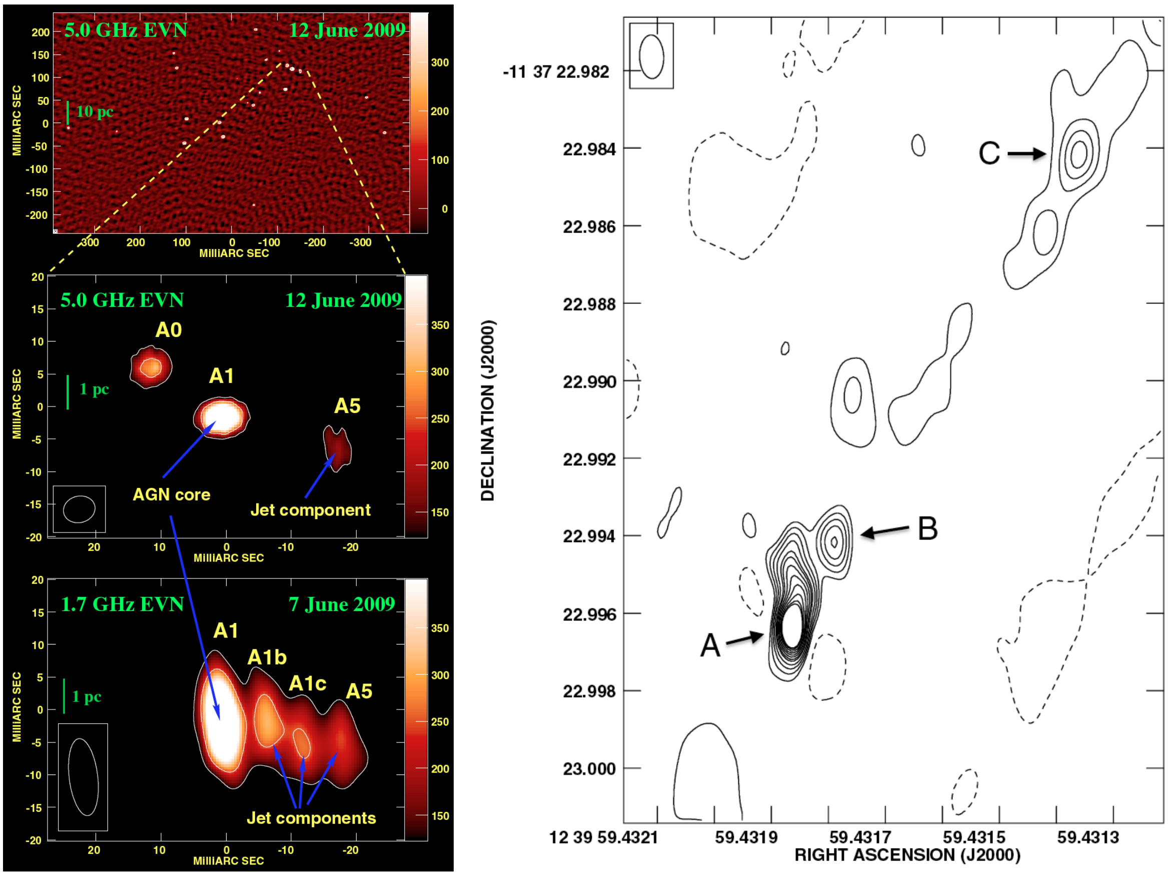

Figure 4: *Left:* European VLBI Network observations of the Arp299-A galaxy from the 100 pc to the parsec scale. The zoomed-in images provide clear evidence of the presence of a jet associated to the LLAGN at the center of the galaxy. Reproduced from [45]. *Right:* VLBA image of NGC 4594 at 23.8 GHz (beam 1.13×0.62 mas), uncovering a 0.6 pc-size mini jet at the core of prototype LLAGN the Sombrero galaxy. Reproduced from [35].

where SKA-MID will deliver excellent sensitivity and angular resolution (almost an order of magnitude better than any other current instrument, e.g. a factor of six better than JVLA, see the SKA1 Baseline Design).

Combining its good angular resolution, nominally ~ 0.25 arcsec at 1.4 GHz, and large collecting area, the SKA will produce HI three dimensional mapps of low redshift AGN, all the way from the central parsecs. This will allow to directly trace the central obscuring material where large HI-equivalent column densities are inferred from X-rays, to the central few hundred parsecs where HI gas discs of these scales. Promising reservoirs for circumnuclear star formation and black-hole fuel are inferred from HI in absorption in some Seyfert galaxies [38].

The excellent sensitivity of the SKA will allow to expand these observations to large samples of AGN at all possible luminosities in the Local Universe. Therefore, the SKA will provide a direct confirmation of large HI-equivalent column densities inferred from X-rays, and will help to asses on the nature of the absorbers. This will provide an stringent test of AGN-tori. The SKA will establish how frequently the central HI discs are present in active and non active nuclei, and uncover the interplay between the neutral gas, the molecular gas structures, and the ionized gas outflows seen at comparable resolutions with ALMA, adaptive-optics assisted IR, and HST observations [52, 43, 37].

7 Relevance of the SKA for AGN studies at parsec scales

Previous sections give an advance of the impact that the SKA will have in the field of AGN, in particular on the study of the parsec-scale region of these objects. The fabulous sensitivity and full-polarization precision (and purity) of the SKA, together with its participation in dedicated high sensitivity VLBI campaigns (see Ros et al. [this book]), will allow to provide (for the first time) robust observational evidence about the actual composition of extragalactic relativistic jets in AGN, as well as the possible existence of the accretion-disc wind (that is postulated to produce most of the initial collimation of the jet) and the actual structure of the magnetic field involved in the jet formation process. It is expected that SKA will implement policies to respond to interesting transient phenomena also observed by facilities covering other spectral ranges. These policies may include extreme flaring states of AGN jets observed with SKA-VLBI. If so, SKA will be an excellent tool for understanding the relation of the different radiation processes in the innermost (and less understood) regions of AGN relativistic jets.

Another of the relevant problems on physics of AGN is about the understanding of the mechanism driving the radio loudness (i.e. the ability to form powerful relativistic jets). The excellent sensitivity and survey speed of the SKA will allow to build huge data sets including millions of AGN at all ranges of radio luminosity to make adequate statistical studies. These are expected to provide definitive answers about this long standing problem. Later, dedicated observations of relevant sources will help constraining the properties of the different components of the AGN (e.g., jets, dusty torus, circumnuclear star formation region, and broad line region), for which high resolution spectral observations of the HI and OH lines will be crucial on the understanding of the three dimensional structures of cold gas in the close vicinity of the AGN. Observations of masers in the innermost nuclear regions of AGN will certainly provide key information about the geometry and dynamics of the accretion discs in AGN at all radio luminosities.

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References

[1] Agudo, I., et al. 2011, ApJ, 726, L13

[2] Agudo, I., et al. 2011, ApJ, 735, L10

[3] Agudo, I., et al. 2014, in proc. "Advancing Astrophysics with the SKA", PoS(AASKA14)093

[4] Alonso-Herrero, A., et al., 2011, ApJ, 736, 82

[5] Alonso-Herrero, A., et al., 2014, MNRAS, 443, 2766

[6] Aloy, M. A., et al. 2000, ApJ, 528, L88

[7] Antonucci, R. R. J. 1993, A&ARA, 31, 473

[8] Asada K., et al. 2008, ApJ, 675, 79

[9] Blandford, R. D. & Payne, D. G., 1982, MNRAS, 199, 883

[10] Blandford, R. D. & Znajek, R. L., 1977, MNRAS, 179, 433

[11] Braatz, J. A., Wilson, A. S., Henkel, C., 1997, ApJS, 110, 321

[12] Burtscher L., et al., 2013, A&A, 558, A149

[13] Davies, R. I., et al., 2007, ApJ, 671, 1388

[14] Díaz-Santos, T. et al. 2007, ApJ, 661, 149

[15] Esquej, P., et al. 2014, ApJ, 780, 86

[16] Fromm, C.M. et al. 2013, A&A, 551, A32

[17] Fromm, C.M. 2015, Spectral Evolution in Blazars: The Case of CTA102, Springer Theses & University of Bonn

[18] Gallimore, J. F. et al. 1999, ApJ, 524, 68

[19] Gallimore, J. F. et al. 2006, AJ, 132, 546

[20] Gómez, J. L., et al. 2011, ApJ, 733, 11

[21] Gómez, J. L., et al. 2012, International Journal of Modern Physics, 8, 265

[22] Hernandez Garca et al. 2014, A&A 569, A26

[23] Hernandez Garca et al. 2015, in preparation

[24] Herrero-Illana, R. et al. 2012, A&A 540, L5

[25] Herrero-Illana, R., et al., 2014, ApJ, 786, 156

[26] Homan, D.C. & Lister, M.L. 2006, AJ, 131, 1262

[27] Hopkins, P. F. & Quataert, E., 2000, MNRAS, 407, 1529

[28] Kinney, A. L. et al. 2000, ApJ, 537, 152

[29] Komissarov, S. S., et al. 2007,MNRAS, 380, 51

[30] Laing R.A., 1981, ApJ, 248, 87

[31] Li, Z.-Y., Chiueh, T. & Begelman, M. C., 1992, ApJ, 394, 459

[32] Lynden-Bell , D. 1969, Nature, 223, 690

[33] Marscher, A. P. et al. 2002, Nature, 417, 625

[34] Marscher, A. P. et al. 2010, ApJ, 710, L126

[35] Mezcua, M. & Prieto, M. A. 2014, ApJ, 787, 62

[36] Molina, S. N. et al. 2014, A&A, 566, A26

[37] Müller-Sánchez, F. et al. 2011, ApJ, 739, 69

[38] Mundell, C. G. et al. 2003, ApJ, 583, 192

[39] Nagar, N. M., Wilson, A. S. & Falcke, H., 2001, ApJ, 559, L87

[40] Nagar et al. 2002, A&A, 392, 53

[41] Nagar, N. M., Falcke, H. & Wilson, A. S. 2005, A&A, 435, 521

[42] Nenkova, M. et al. 2008, ApJ, 685, 160

[43] Orienti, M & Prieto, A. M. 2010, MNRAS 401, 2599

[44] Paragi, Z., et al. 2014, in proc. "Advancing Astrophysics with the SKA", PoS(AASKA14)143

[45] Perez-Torres, M. et al. 2010, A&A 519, L5

[46] Ramos Almeida, C., et al., 2009, ApJ, 702, 1127

[47] Ramos Almeida, C., et al., 2011, ApJ, 731, 92

[48] Schmitt, H. R. et al. 2001, ApJS, 132, 199

[49] Seyfert, C. K. 1943, ApJ, 97, 28

[50] Shakura, N. I. & Sunyaev R. A.1973, A&A, 24, 337

[51] Sol, H., Pelletier, G. & Asséo, E. 1989, MNRAS, 237, 411

[52] Storchi-Bergmann, T. et al. 2010, MNRAS, 402, 819

[53] Storchi-Bergmann, T., et al. 2012, ApJ, 755, 87

[54] Tristram, K. R. W. et al., 2009, A&A, 502, 67

[55] Vlahakis, N. & Königl, A., 2004, ApJ, 605, 656

[56] Zamaninasab, M. et al. 2013, MNRAS, 436, 3341