The innermost regions of Active Galactic Nuclei – from radio to X-rays

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Summary. Active Galactic Nuclei can be probed by at different regions of the electromagnetic spectrum: e.g., radio observations reveal the nature of their relativistic jets and their magnetic fields, and complementarily, X-ray observations give insight into the changes in the accretion disk flows. Here we present an overview over the AGN research and results from an ongoing multi-band campaign on the active galaxy NGC 1052. Beyond these studies, we address the latest technical developments and its impact in the AGN field: the Square Kilometre Array, a new radio interferometer planned for the next decade, and the oncoming X-ray and gamma-ray missions.

1 Background

The standard model for Active Galactic Nuclei (AGN) proposes that the energy release is produced by the accretion of matter onto super-massive black holes (BH) [11, 44, 45]. The AGN is powered by the conversion of gravitational potential energy into radiation, although the rotational kinetic energy of the BH may also serve as an important source of energy [36, 64, 37]. A fraction of the matter is ejected via a poloidal magnetic field in a jet perpendicular to the accretion disk surrounding the black hole.

A region of gas with broad emission lines is located close to the accretion disk. Narrow-line emitting clouds are present outside the disk and torus region. AGN unification models [1] presume that depending on the viewing angle of the torus-disk-jet complex the observed galaxy appears as a blazar when the

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jet points towards the observer; as an object like Seyfert 1, Broad-Line-Radio Galaxy or Quasi-Stellar Object for intermediate angles; or as a Seyfert 2 or a Narrow-Line-Radio Galaxy when the jet lies in the plane of the sky. For a phenomenological taxonomy of the AGN zoo, see e.g. Table 1.2 in [40].

The powerful jets observed commonly in radio-loud AGN [74] consist of relativistic (shocked) plasma which may extend up to kiloparsec scales (showing typically extended radio lobes [56, 6]), much larger in size than their host galaxies. Jets oriented close to the line of sight have favourable observing conditions due to relativistic boosting.

Emission from AGN can be observed throughout the electromagnetic spectrum: The jet synchrotron emission can be probed by radio and millimetre observations. The brightest jets emit also in the optical (e.g., [3]) and in X-rays [17]. The thermal emission of the accretion disk and the surrounding torus are probed both in temperature distribution and in morphology by infrared interferometry (e.g., [23]). The broad and narrow emission line regions are studied by optical spectroscopy. X-ray imaging and spectroscopy probe the corona, the accretion disk, and the jet radio lobe region at kiloparsec-scales as well as compact jets in blazars. Shocked regions in the jet, where the plasma is hotter, can emit at energies of up to γ-rays [55].

Presently, different tools are available for the astronomers to probe the nature of AGN. The spectral energy distribution can be split into several components produced by distinct emission mechanisms (synchrotron, inverse Compton, thermal, etc.) and affected by absorption. Spectroscopy of the Fe Kα X-ray emission (the strongest fluorescent line due to the highest cross section for the absorption of all iron atoms less ionised than Fe^{+16}) probes the relativistic accretion disk. This line was first detected in radio-quiet (Seyfert 1 type) galaxies (e.g., MCG–6-30-15 [68]). The “louder” the galaxy is at radio wavelengths, the weaker the iron line tends to be. A thermal “bump” is usually present in the optical and ultraviolet continuum spectrum. Spectroscopy of the broad and the narrow line regions provides information about the pressure of the medium around the jet. Measurements of the variability of radio sources yield limits on the size of the emitting regions (from the smallest timescales of variations). Radio- and millimetre-wave imaging at the highest resolutions (very-long-baseline interferometry: VLBI) provide resolutions down to 0.1 milli-arcsec, reaching typically sub-parsec scales. This shows the jet structure at the innermost region of the AGN. At the highest frequencies, the emission from the jet base (core) is unveiled [41, 43]. Measurements of the polarisation reveal changes in the magnetic fields present at the jet.

Single-dish flux-density and spectral monitoring programs probe absorption effects and the presence of different synchrotron-emitting features in the jets. These are complemented by X-ray monitoring to probe the accretion disk via spectroscopy and imaging. These aspects will be expanded in the next sections. First we give an overview on the extensive work being performed on AGN at different wavelengths, then we will describe an ongoing campaign on the active galaxy NGC 1052, and finally we will provide some prospective view
of future observations with the Square Kilometre Array and new X- and γ-ray missions.

2 Observing the multi-waveband sky

Pioneering work combining VLBI and X-ray observations was performed already in the 1970s [47]. Important landmarks in this research are, for instance, the combined radio and X-ray observations on the quasars 3C120 [48] — where the X-ray flux drops for days to weeks just prior to the ejection of bright features in the jet, and PKS1510–089 — where a superluminal ejection in the jet occurred immediately after the start of a major X-ray and optical outburst in late 2000 [49].

AGN surveys are an essential tool for finding and identifying appropriate candidates for successful combined X-ray and radio studies. Ref. [44] summarises most of the ongoing surveys in VLBI, radio monitoring, infra-red, optical, X-ray and γ-ray wavelengths.

VLBI is a well-established technique. Four decades have elapsed since the first experiments (e.g., [32]), and the discovery of superluminal motions [73, 8] took place thirty years ago. The exploration of the radio sky on parsec-scales has been facilitated dramatically since the construction of the Very Long Baseline Array (VLBA) in the mid 1990s. Starting with the regular observations of the VLBA a program to monitor the jet kinematics of the most prominent radio-loud AGN (over hundred) in the northern sky was defined and initiated in 1994. This was the 2 cm Survey [33, 75, 35, 39], continued since 2002 as the MOJAVE program [42, 20] — the latter including also linear and circular polarisation monitoring.

X-ray astronomy is also a relatively young science, experiencing a new revolution with every new generation of X-ray missions. After ASCA (1993–2001, [67]) and BeppoSAX (1996-2003, [5]), the missions Chandra (since 1999 [72]), XMM-Newton (since 2001 [25]), and Suzaku (since 2005 [54]) constitute the state of the art for X-ray imaging and spectroscopy at present.

X-ray emission from the sources of the 2 cm Survey and the MOJAVE samples has been studied in detail from the available archival data [28]: 2cm-X-sample, was established by making use of all publicly available archival data from the first four missions mentioned above. Originally with 50 sources, the sample is being completed by a Swift program to observe the remaining 83 objects from the MOJAVE sample [29].

In the following section we report on the multi-wavelength monitoring campaign on one particular source from the 2cm-X-Sample, the active galaxy NGC 1052.

2.1 NGC 1052: the key to jet-disk coupling

The nearby elliptical galaxy NGC 1052 can be classified as a radio-loud object [27]. It hosts a twin-jet system oriented close to the plane of the sky (e.g.,
NGC 1052 has been classified as the prototypical low-ionisation nuclear emission region (LINER). This source is particularly suited for connecting radio and X-ray observations, since it shows an edge-on accretion disk, water maser emission, an obscuring torus (see below), and it hosts mildly relativistic jets that can be probed by VLBI.

Detailed multi-wavelength observations at the centimetre range provide evidence for an obscuring torus covering partially the western, receding jet [34, 31, 27]. The column densities measured in the radio and X-rays have comparable values [26]. In X-rays the source shows a flat spectrum and a soft excess [71, 15, 16, 26]. Sub-parsec imaging of both jets by VLBI from the 2 cm Survey/MOJAVE programme [70] revealed motions of 0.26c. A new jet feature is ejected every 3–6 months, correlated with flux density outbursts.

There are indications [28] that the ejection of a new feature in the jet, estimated to occur in Epoch 2001.0, is associated with the change of the relativistic line profile from data taken by BeppoSAX ([16], reanalysed in [28]) at epoch 2000.03 and by XMM-Newton at epoch 2001.62, where the line is broadened. This is the first detection of a highly relativistic iron line in a radio-loud AGN with a compact radio jet. The variability of the iron line and of the fraction of accreted energy that is channeled into the jet could be related to changes in the structure of the magnetic field in and above the accretion disk.

Given this scenario, we initiated in mid 2005 a multi mission campaign to track the birth of new VLBI components at the base of the jet and counter-jet, to compare those with the flux density monitoring and spectroscopy in radio and X-rays and to establish cause-effect relationships in a much more confident way than the accretion-ejection event reported previously [28]. This campaign includes, in X-rays: a) Rossi X-Ray Timing Explorer (RXTE) flux density monitoring at 2-10keV: 30 epochs of 2 ks each, scheduled every three weeks; b) Chandra imaging and spectroscopy: one deep observation in Sep 2005; c) XMM-Newton imaging and spectroscopy: one triggered observation in Feb 2006 so far. The source is also being monitored by the Burst Alert Telescope (BAT; see [4]) on-board Swift since the beginning of 2005 (see below). Radio observations include: a) $\lambda\lambda 13/6/3.6/2.8/2/1.3/0.9$cm dedicated light curves taken by the 100-m radio telescope in Effelsberg, with ca 70 h observations scheduled every three weeks; b) $\lambda\lambda 31/13/7.7/6/3.9/3.6/2.7/2/1.4$cm light curves taken by the RATAN-600 and the Univ. of Michigan Radio Astron. Obs. (UMRAO, [2]) in the framework of long-term monitoring programs; and c) $\lambda\lambda 13/7$mm Very Long Baseline Array imaging, with 18 observing runs of 6 h each scheduled every six weeks (images from the first epochs are presented in [62]).

RXTE Monitoring The Rossi X-ray Timing Explorer (RXTE) is monitoring NGC 1052 since mid 2005 with pointings of 2 ksec each every three weeks. We concentrate on the analysis of the data from the PCA detector [24]. The
data were reduced with the REX script\(^5\) that simplifies the reduction of large amount of data, with standard criteria for faint sources. We used the data of PCU 2 and layer 1 which provide the best signal-to-noise ratio. For the spectral analysis we used xspec version 11.3. We restricted the analysis to the energy range 2–10 keV and fitted an absorbed power law with a fixed value for the Galactic absorption of \(N_H = 2.95 \cdot 10^{-20} \text{ cm}^{-2}\)\(^{30}\).

\(^5\) See http://heasarc.gsfc.nasa.gov/docs/xte/recipes/rex.html
spectrum (e.g., the soft excess, and the reflection component), as well as due to changes of the primary power-law continuum component or the absorption. A more careful analysis of the RXTE data with the detailed spectral composition coming under scrutiny from the deep pointings of XMM-Newton and Chandra is underway.

The RXTE monitoring data show a systematic increase of flux mid to end 2005 by more than a factor of 2 followed by a dramatic drop around epoch 2006.1. After that, the source flux rises again over several months. With the present data, it is difficult to judge whether this sampled portion of the light curve corresponds to two outbursts. Alternatively, the data could be interpreted as showing two long dips similar to the ones in 3C 120 [49] but on longer time scales. The photon index $\Gamma$ is found to vary most of the time between 1.4 and 1.8, values that are typically seen in Seyfert galaxies. It is interesting to note that the historically well-known “unusually flat X-ray spectrum” of NGC 1052 [71, 16, 26, 27] is found only during two relatively short time periods in Sep/Oct 2005 and Feb/Mar 2006. These both epochs coincide with the beginning of a rise in the X-ray flux, indicating that either flares occur first at high energies, or vice-versa that the dips last longest in the soft band.

Swift BAT Monitoring Figure 1 b) shows the hard X-ray image (15–150 keV) of NGC 1052 from the first 16 months of Swift BAT monitoring observations [46]. The source is clearly detected with a formal significance of $>5\sigma$. Unlike the lower-energy bands (radio, soft–medium X-rays), the BAT light curve (Fig. 1 c) shows only marginal variability on time scales of months at hard X-rays. Note that negative count rates can statistically result from the subtraction of two almost equal numbers in the background-dominated limit and that large error bars indicate periods of low exposure in the region of NGC 1052 on the sky. For these two reasons, the negative value at $\sim$ 2005.6 should not be over-interpreted. The perhaps more significant feature is the decrease and subsequent increase in the first three months of 2005. From mid through end 2005, the hard X-ray flux of NGC 1052 was quasi-constant within the sensitivity limit of BAT.

The monitoring of NGC 1052 at hard X-rays will continue throughout the regular all-sky observations of BAT. This represents a further valuable component in our monitoring campaign of this source. Both long-term trends and putative higher-amplitude variability on shorter time scales (e.g., due to SSC flares) will be detectable and can be analysed in view of the variability patterns at lower energies. In particular, it shall be noted that BAT is sensitive enough and that NGC 1052 is bright enough in the 15–150 keV band to detect variability if it occurs with the same amplitude as in the RXTE band. Thus, even a lack of variability through 2006 in the BAT light curve would put an important constraint on the nature of the nuclear activity in NGC 1052 by attributing most of the variability to a spectral component at soft X-ray energies.
**RATAN-600 Radio Spectra** We started the long-term monitoring of 1–22 GHz radio spectra of NGC 1052 at the 600 meter ring radio telescope RATAN-600 of the Russian Academy of Sciences in 1996. The observations of continuum spectra are done almost instantaneously at 1, 2.3, 3.9/4.8, 7.7, 11.1, and 22 GHz in a transit mode, 2–4 epochs per year. Details of the observations and data processing can be found in Ref. [38].

Selected RATAN-600 instantaneous continuum spectra over the last 10 years of observations as well as the data accumulated during the time of our multi-frequency campaign until mid 2006 are presented in Figure 1 c) & d). The flux density at frequencies over 10 GHz has dropped by a factor of 2 since the start of the campaign. The observed flaring variability is most probably due to production and evolution of new parsec-scale features dominating in the synchrotron spectrum of the compact jet. The flare spectrum peaks around 10 GHz in 2005, with SSA radiation below the peak. The characteristics timescale of the observed long-term radio variability of NGC 1052 is several months.

**Summary of Some Early Results from the NGC 1052 Monitoring Campaign**

The monitoring campaign of NGC 1052 begun in mid 2005 and is en route to a scrutiny of the jet-disk coupling in this active galaxy. For one-and-a-half years now, the jet-production activity has been monitored at sub-milli-arcsecond angular resolution with the VLBA at 22 and 43 GHz [62]. Over this period, the source was constantly active in the radio. Its radio spectrum has been monitored every three weeks in the cm regime with the Effelsberg 100-m telescope, and within the long-term monitoring programs at the University of Michigan and with RATAN-600. We are in the process of making a detailed analysis of these data. This will enable us to compare the jet-production activity to accretion-disk probing observations at high energies.

Our preliminary analysis of the first 1.5 years of RXTE monitoring data reveals for the first time the previously missing piece of evidence that the 2–10 keV X-ray spectrum of NGC 1052 is variable on essentially the same time scales as the radio emission. While a continuation of the monitoring over several variability cycles is important for quantifying this finding. The present data support the idea that the X-ray and radio components may be directly (or indirectly) coupled. In this context, it is important to consider our earlier finding that the iron-line in NGC 1052 has varied along with a major jet-ejection event [28] on exactly these time scales in 2000/2001. Additional deep X-ray spectroscopic observations with XMM-Newton and/or Suzaku will likely be able to find very different X-ray spectral states in terms of both the continuum and the iron-line and can be interpreted in view of the continuously monitored jet-production activity. In particular Suzaku, with its high effective area at ~ 6 keV and its broad band pass that covers also the hard X-ray regime, will yield important constraints on the iron line and will at the same time be able to reconcile the RXTE and XMM-Newton results with the Swift BAT results.
3 Instruments for the future

In this section we discuss the prospectives for AGN research in the radio and X-rays under the light of the astronomical facilities planned for this and the next decade.

Radio: the Square Kilometre Array Two new radio facilities will be available in the near future: operating at very long wavelengths, the Low Frequency Array in The Netherlands (LOFAR, [61]), and the Atacama Large Millimetre Array in Chile (ALMA, [7]) at the sub-millimetre range. In the cm-band, the Square Kilometre Array (SKA, [63, 69, 9]), a new facility reaching 100 times better sensitivity at milli-arcsec-resolution is planned for the next decade. The scientific case of the SKA requires a radio telescope with sensitivity to detect and image atomic hydrogen at the edge of the universe, which requires a very large collecting area. The new instrument should have a fast surveying capability over the whole sky, which makes a very large angular field of view mandatory. It should have capability for detailed imaging of the structures at the sub-arcsecond level, for which a large physical extent is needed. Finally, a wide frequency range is needed to handle the different scientific goals. The concept which fills these requirements implies a square kilometre collecting area in an interferometer array, with a sensitivity two orders of magnitude larger and a survey speed four orders of magnitude larger than the Expanded Very Large Array. The proposed frequency range should cover from 0.1 to 25 GHz, with baselines up to 3000 km, and a field-of-view of 50 square degrees at frequencies lower than 1 GHz. This project would cost over one billion euros with a running cost of around seventy million euros per year. The so-called Phase 1 of the project should be ready in 2012, and the complete array at the end of the 2010s. The short list of site candidates favours a location in Southern Africa or Western Australia. A reference design [22] has been developed recently, including three system types to be combined in hybrid elements. The reference design includes a sparse aperture array (0.1–0.3 GHz, a.k.a. as “Era of Recombination” array, similar to LOFAR, providing wide and multiple independent field-of-views), a dense aperture array (0.3–1 GHz, a.k.a. radio “fish eye” lense with all-sky monitoring capability), and a small-dish and “smart-feed” array (0.3–25 GHz, a.k.a. “radio camera”, with ∼10-m dishes and wide response feeds). More information on the project can be found under http://www.skatelescope.org.

The SKA will image all radio galaxies in the sky to the micro-jansky level, especially probing active galaxies in the radio-quiet regime (e.g., the Seyfert galaxies exhibiting broadened iron lines in X-Rays). The project will signify a revolution in observational cosmology, in the studies of the magnetic universe, etc., but will also enable a completely new view of the traditional targets of VLBI research: active galactic nuclei.

High-energy missions Research at high energies will reach new frontiers in coming years with the missions currently being put into operation or planned (see [57] for a recent review on X-ray missions):
Suzaku (since 2005) is specifically designed to study the Fe Kα line. Its broad band pass from 0.3 keV to > 100 keV combined with its high effective area at ~ 6 keV and the good spectral resolution makes it possible to determine the continuum model and at the same time measure the iron K line. A recent review of Suzaku observations of iron lines in AGN can be found in [60].

Within its blazar key project, the X-Ray Telescope (XRT) of Swift is currently obtaining a large number of X-ray spectra of radio-loud, core-dominated AGN, many of which have never been observed in the soft X-ray regime since ROSAT in the 90s and many never above 2 keV. In particular, Swift is going to complete the 2-cm-X-Sample of X-ray observed MOJAVE sources [28], the 133 radio-brightest compact AGN in the northern sky. Swift is particularly well suited for such a large pointed-survey program because of its flexibility. It will greatly enhance our knowledge of radio-loud AGN X-ray spectra by providing a VLBI-defined statistically complete set of X-ray (and UV) spectra. This will be particularly valuable to identify more sources similar to NGC 1052 for combined VLBI and high-energy studies.

The next planned major step for X-ray observations of AGN will be Constellation-X [21]. The current mission design of Con-X foresees a sensitivity of > 50 times better than XMM-Newton and Suzaku. The mission will provide the highest spectral resolution to date by making use of calorimeter detectors. These will be particularly important for fine-scale studies of relativistic broad iron lines in AGN. With Con-X, it will be possible to obtain high-quality X-ray spectra of accreting super-massive black-hole systems in short snapshot observations. For sources like NGC 1052, this means that it will be possible to perform high-sensitivity accretion-disk monitoring with a minimum of required telescope time. At the other end of the electromagnetic spectrum, the SKA will for the first time provide the possibility to study in detail the radio cores of Seyfert galaxies and other radio-quiet AGN. Together, Constellation-X and the SKA will allow us to perform high-sensitivity combined radio and X-ray studies of AGN, both radio-loud and radio-quiet.

In the hard X-ray regime, the all-sky monitoring Energetic X-ray Imaging Survey Telescope (EXIST; [14]) would yield a sensitivity a factor 50–100 higher than Swift/BAT at the 5–600 keV. The science goal of EXIST is the discovery and study of black holes on all scales from stellar-mass to super-massive black holes. In the context of hard X-ray blazar studies, EXIST is expected to boost the number of observationally accessible sources (e.g., only about 10% of the MOJAVE blazars are bright enough to be detected by BAT after 16 months of observations, while we expect most if not all MOJAVE sources to be easily detectable by EXIST). For the study of sources like NGC 1052 that are bright enough to be studied already today by the BAT (see above), EXIST will dramatically increase the time resolution and decrease the minimal detectable variability amplitudes.

At even higher photon energies, the new γ-ray facility GLAST (Gamma-ray Large Area Space Telescope; [13]) will be launched in late 2007. It follows in
10 Ros, Kadler, Kaufmann et al.

the footsteps of the Compton Gamma Ray Observatory (CGRO; 1991-1999) whose main instrument EGRET has discovered that blazars and flat spectrum radio quasars are strong $\gamma$-ray emitters [12]. The third EGRET catalog of high-energy $\gamma$-ray sources [18] originally contained 66 high-confidence identifications with blazars. Among the statistically complete MOJAVE sample of the 133 radio-brightest compact AGN in the northern sky, 44 have a high-probability EGRET identification according to revisions of the EGRET-blazar sample [51, 52, 65, 66]).

While the detailed mechanism for the production of gamma-ray emission has not yet been agreed upon, it is widely accepted that the $\gamma$-ray emission from blazars is highly beamed and anisotropic [10]. It probably takes place close to the central engine or at the base of the relativistic jet. VLBI observations provide the best imaging probes close to the central engine, so that one expects to find differences in the milliarcsecond-scale radio properties and kinematics between EGRET-detected and not-detected sources. Indeed, [35] find that radio jets that are also strong $\gamma$-ray sources have faster jets than EGRET undetected sources. Furthermore, recent work [39, 42] indicates that EGRET sources have more compact radio cores and more highly polarised and more luminous jet features than non-EGRET sources. In the GLAST era, it will be possible to investigate these findings in unprecedented detail.

The EGRET counterpart on-board GLAST will be the LAT (Large Area Telescope) whose capabilities are specifically well-suited for blazar-variability studies (e.g., [53]). The highly superior sensitivity and angular resolution of LAT is expected to result in the detection of thousands of new $\gamma$-ray sources, in particular it is expected that the LAT will be able to monitor the $\gamma$-ray light curves of hundreds of bright blazars with high temporal resolution. Various efforts in the radio regime are being made to exploit the opportunities offered by this mission: in particular, within the MOJAVE project, it is planned to trigger VLBI monitoring observations by GLAST/LAT detected $\gamma$-ray flares, to relate the flaring activity with ejections in the radio jet. It will also be possible to use GLAST/LAT light curves as jet-activity monitors. For sources like 3C 120 or NGC 1052, whose mass-accretion can be monitored via X-ray observations, this will open a new avenue to jet-formation studies.

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