Probes of Jet-Disk-Coupling in AGN from combined VLBI and X-Ray Observations

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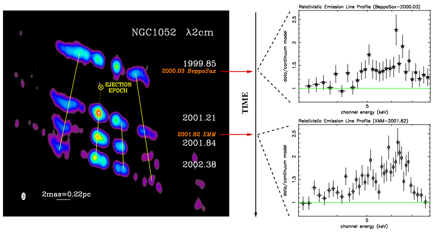
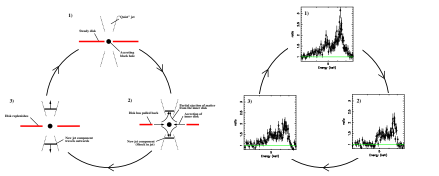
The formation of powerful extragalactic jets is not well understood at present as well as the key question: "What makes an AGN radio loud?". Radio-loud AGN offer the unique possibility to image the small-scale structure of extragalactic radio jets via Very Long Baseline Interferometry (VLBI). The study of relativistically broadened iron lines in the X-ray regime allows the very closest neighbouhood of the black hole to be explored: its accretion disk, which is thought to provide the "fuel" for the jet ejection. The time variability of the iron line profile from the center of the LINER galaxy NGC 1052 discloses an association with the ejection of new components into the parsec-scale jet. NGC 1052 is the only example of a radio-loud, core-dominated AGN so far, that exhibits strong broad iron line emission. Here we discuss how the combined application of VLBI- and X-ray spectroscopic observations allow the inter-relation between the accretion flow and the formation of relativistic jets in AGN to be explored.



Variable X-ray iron line profile of NGC 1052 before and after the ejection of a new VLBI jet component.

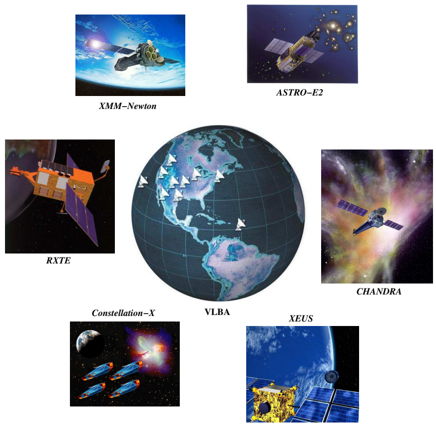
The Broad Iron Line in NGC 1052

The first detected relativistic, broad iron line in a radio-loud AGN is emitted from the accretion disk of the nearby active galaxy NGC 1052 (Kadler et al., submitted). The line profile is measured at two epochs from observations with the *XMM-Newton* X-ray telescope and the *Beppo*Sax satellite. The radio jet of NGC 1052 has been monitored systematically (with a linear resolution smaller than a tenth of a parsec) with VLBI observations over more than a decade (Vermeulen et al. 2003, A&A 401, 113) within the scope of the VLBA 2 cm Survey (`www.nrao.edu/2cmsurvey`). A violent ejection of relativistic plasma in the radio jet, was accompanied by pronounced variability of the broad iron line: **the source was caught in the act of feeding a part of the accretion disk into the black hole while a fraction of the material was injected into the jet.**



Left: Sketch of the accretion–ejection event observed in NGC 1052. Right: Simulated 30 ksec *XMM-Newton* iron-line profiles for three different stages during the accretion–ejection event.

A physical model of the accretion–ejection event in NGC 1052: **1)** Before 1999 a steady, optically thick accretion flow feeds the central black hole and a broad iron line is emitted between ∼3 keV and 8 keV and a part of the accreting matter maintains a twin jet. **2)** A dramatic event within the accretion flow in late 1999 disrupts the inner accretion disk. This results in a depression of the relativistic "red wing" of the iron line and a decrease of the fluorescing disk area as observed with *Beppo*Sax. A substantial amount of the inner disk material is accreted onto the black hole, while a fraction of the same material is ejected into the jet. **3)** The new jet component becomes first visible in the VLBI image at epoch 2001.21 while the inner disk slowly replenishes. The broad, relativistic line profile recovers and is visible during the August 2001 *XMM-Newton* observation with a strong "red wing".

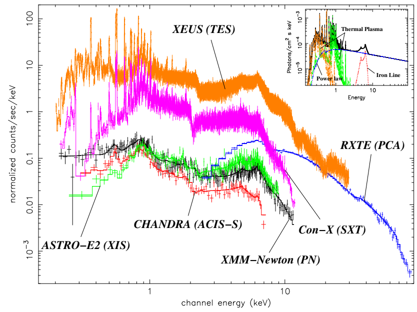


Present and future X-ray missions suitable for combined VLBI- and X-ray spectroscopic observations of radio-loud AGN.

The Future of Combined VLBI- and X-Ray Studies of AGN

Future studies of NGC 1052: NGC 1052 is the only radio-loud AGN with strong broad iron line emission detected so far. This makes NGC 1052 the key object for future studies, which address the open questions of black hole accretion and jet formation. A dedicated monitoring campaign of NGC 1052 with I) high frequency VLBI observations and II) high signal-to-noise X-ray spectroscopic observations provides the ideal approach towards a better understanding of AGN physics. Sample profiles of the relativistic iron line can be taken with *XMM-Newton* and/or *ASTRO-E2*, while the *Rossi X-ray Timing Explorer* (*RXTE*) can serve as a continuum monitor for short- and long-term X-ray flux variability.

Future Radio Astronomy Developments: The performance of VLBI observations is being continuously improved towards higher frequencies (yielding higher resolution) and higher sensitivities. Particularly, an oncoming Square Kilometer Array (SKA), capable of operating at high frequencies with long baselines, will provide a breakthrough in sensitivity. This will allow a much larger number of AGNs, particularly some radio-quiet (i.e., weak) objects, to be accessed.



The measured 13 ksec *XMM-Newton* spectrum and simulated 13 ksec spectra from *CHANDRA*, *RXTE*, *ASTRO-E2*, *XEUS*, and *Con-X*. The spectral model consisting of absorbed plasma, power-law, and iron-line emission is shown in the inset panel.

Future X-ray observatories: A significant improvement of black-hole accretion and jet formation studies in AGN will come from future X-ray observatories. With *Con-X* and *XEUS* the sensitivity of broad iron line studies will increase dramatically. This will allow other radio-loud AGN with considerable broad iron line emission to be detected. Direct comparison of the accretion flow properties in radio-loud and radio-quiet AGN will allow the unsolved mystery of the radio loud/quiet phenomenon to be attacked, or in other words to address the question: **"What leads some supermassive black holes to launch powerful relativistic jets?"**

ASTRO-E2 (Launch: 2005): The recovery mission for the *ASTRO-E* spacecraft (lost after launch in February 2002) will cover the energy range 0.4 keV to 600 keV with three instruments, an X-ray Spectrometer (XRS), an X-ray Imaging Spectrometer (XIS), and the hard X-ray detector (HXD). It will yield high X-ray spectral resolution throughout the iron line emission energy range.

Constellation-X (Launch: 2015–2017): *Con-X* is designed to have a factor of 100 increase in sensitivity over current X-ray spectroscopy missions. *Con-X* is ideal for studying the short-term variability of the Fe K line profile in AGN and to measure the effects of strong gravity near the event horizons of black holes.

XEUS (Launch: 2014): The *X-Ray Evolving Universe Spectrometer* (*XEUS*) is planned as the follow-on to *XMM-Newton*. It will be a permanent space-borne X-ray observatory with an unprecedented sensitivity in the X-ray regime, around 200 times more sensitive than *XMM-Newton*. During the expected lifetime of more than 20 years, several upgrade cycles are planned (e.g., the collecting area will be expanded from 6 m^2 to 30 m^2 at 1 keV).

This work is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and the U.S.A. (NASA). We have made use of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA's Goddard Space Flight Center. The VLBA is an instrument of the U.S.A. National Radio Astronomy Observatory, which is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc. This reasearch has made use of data obtained within the VLBA 2 cm Survey collaboration. M. K. was supported for this research through a stipend from the International Max Planck Research School (IMPRS) for Radio and Infrared Astronomy at the University of Bonn.