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AGN Science: The Past, The Present, The Future

AGN Science

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Abstract. I review some basic results on AGN science by concentrating on the Fe K and Fe L line observations and on the Narrow-Line Seyfert 1 physics. This paper is based on a talk given at the Vulcano workshop, 'The multifrequency behavior of high energy cosmic sources' in 2009. Given the length of the talk and the number of pages the review on AGN science cannot be complete and is biased towards two science topics and my personal view.

Key words. AGN: general

1. Introduction

The study of relativistically broadened Fe K and L lines in AGNs can be used as a diagnostic tool of the geometry of the accreting matter at the innermost stable orbit as well as of the spin of the black hole through the gravitational redshift. Since the discovery of the first relativistic line in MCG-6-30-15 (Tanaka et al. 1995), broad iron lines have been found in a few other Seyfert galaxies (e.g. Nandra 2008). Narrow-Line Seyfert 1 galaxies (NLS1s) are type 1 Seyfert galaxies with FWHM values of the Hβ lines smaller than 2000 km s^{-1} and strong Fe II multiplet emission (Osterbrock & Pogge 1985). Recent X-ray observations have greatly advanced the study of ultrasoft NLS1s and have revealed strikingly clear correlations between optical emission line properties and the shape of the X-ray continuum. NLS1s are generally characterized by steep soft X-ray spectra with photon indices for simple power law fits up to about 5. Detailed spectral modeling shows that Narrow-Line Seyfert 1 galaxies often have very strong soft X-ray excess components compared to their hard X-ray tails. A clear anticorrelation is found between the ROSAT spectral softness and the Hβ FWHM in type 1 Seyferts (Boller et al. 1996, Brandt et al. 1997) and quasars (Laor et al. 1997). This is remarkable as the X-ray spectra of most Seyfert 1 type galaxies are formed predominantly within ≈ 50 Schwarzschild radii of their black holes, while Seyfert optical permitted lines are formed in a separate and significantly larger region. It appears that the anticorrelation between Hβ FWHM and ROSAT spectral softness is due to a primary underlying physical parameter: high ratios of the accretion rate to the black hole mass, orientation and black hole spin have been suggested. NLS1s are ideally suited to study the physics of the innermost regions of AGNs.

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2. The Past

2.1. Fe K lines history

The first detections of Fe K line emission in Seyfert galaxies were obtained with the Japanese Ginga satellite (Pounds et al. 1990, Nandra et al. 1994). A Compton reflection hump was detected above an underlying power law. This was interpreted as the reflection of hard X-ray photons on optically thick matter and as an evidence for the presence of an accretion disc surrounding the black hole. The Fe K line was first resolved by the ASCA satellite. A strong asymmetric line profile was observed in the Seyfert galaxy MCG-6-30-15 (Tanaka et al., 1995, c.f. Fig. 1 of this paper). The velocity of the matter close to the last stable orbit is about one third of the velocity of the light. Another discovery is refered to as the 'X-ray Baldwin effect'. The equivalent width of the Fe K line is inversely correlated with the X-ray luminosity. The physical interpretation is that higher X-ray luminosities are most probably due to higher ionized accretion disks. In this case the neutral Fe K line photons are emitted in a significant Thompson depth and suffer Compton-broadening when reaching values of the Thompson depth close to one.

2.2. NLS1 history and science

The first notice on the presence of NLS1s was in 1971. Zwicky (1971) reported on an optical outburst in I Zw1. Extreme X-ray variability has been detected later (see below), but there is no other report on extreme optical variability in NLS1s. The optical variability of NLS1s is less pronounced compared to brood-line Seyfert 1 galaxies. The first note on the narrow optical permitted lines was published by Davidson and Kinman (1978). The authors point out that the optical spectrum of the Seyfert galaxy Mrk 359 shows unusually narrow permitted lines and that this 'unusual' object merits further observations. Osterbrock and Dahari (1983) initiated a systematic investigation of NLS1s. In 1985 Osterbrock and Pogge came up with the definition for NLS1s. First, the permitted optical lines are only slightly broader than the forbidden lines. Second, the objects show strong optical Fe II multiplet emission, and third, the ratio of [OIII] to Hβ is smaller than 3. Goodrich (1989) added that the FWHM of the Hβ line is smaller than 2000 km s^{-1}. In 1989, Stephens found a high fraction of NLS1s in X-ray samples and pointed out that 'X-ray selection may be an effective way to find NLS1s'. The first report on steep soft (0.1-2.4 keV) photon indices in NLS1s was published by Puchnarewicz (1992) based on ROSAT data. A relation between the soft X-ray continuum and the optical line width was published in 1996 by Boller, Brandt and Fink. While broad-line Seyfert 1 galaxies have their photon indices confined to a fairly narrow range of about 2.3 with a small scatter, the photon indices rise up to values of about 5 for FWHM of the Hβ line below 2000 km s^{-1} (c.f. Fig. 8 of Boller et al. 1996). The physical interpretation of this result is that the emission from the accretion disk determines the velocity distribution in the BLR. Finally, Laor (1997) extended the study of the line width- soft photon index relation to higher luminosities typical for quasars.

These observations resulted into a Seyfert 1 unification through physical processes. The strong emission from the accretion disc in NLS1s is most probably due to a higher accretion rate compared to broad-line Seyfert 1 galaxies, which show weak emission from the accretion disc. The steep 2-10 keV photon indices in NLS1s (Brandt, Mathur and Elvis 1997) are thought to be due to Compton cooling of the accretion disk corona. The narrow optical Hβ lines are due to lower black hole masses compared to broad-line Seyfert 1 galaxies (Boller et al. 1996) which is confirmed by reverberation measurements of the line response in the BLR. NLS1s show weaker [O III] emission compared to broad-line Seyfert 1 galaxies. The strong disk emission results into a larger BLR radius in NLS1s and to a larger filling factor and absorption of the accretion disk photons by BLR clouds. The strong optical Fe II multiplet emission in NLS1s might be due to the strong disc emission. To ionize Fe I to Fe II X-ray photons are required as the Fe II multiplet emission arises in regions with densities larger than 10^9 cm^{-3}. As NLS1s emit

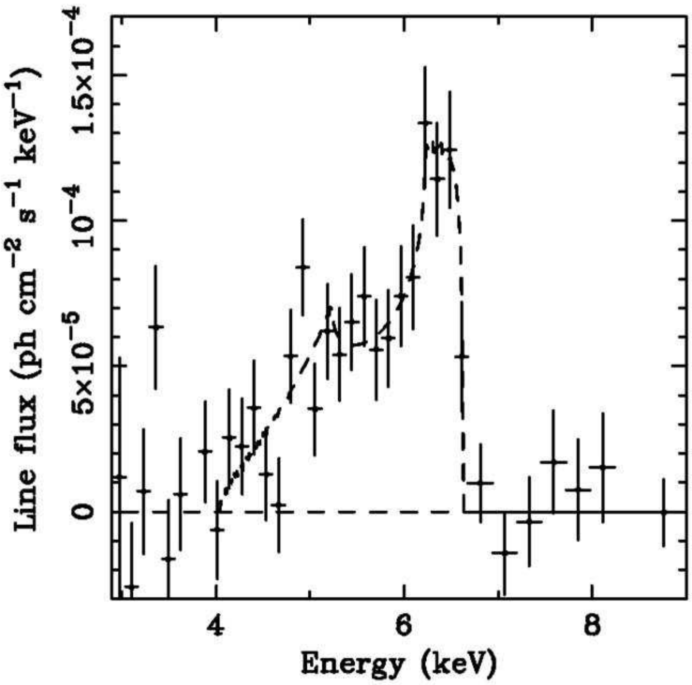

Fig. 1. The first detection of a relativistic Fe K line in the Seyfert galaxy MCG-6-30-15 by Tanaka et al. (1995, reprinted with permission from Nature, License Number: 2413640463826). The characteristic double-horned line profile is clearly visible. The velocity of the matter at the last stable orbit is about one third of the velocity of light. These results are interpreted as the detection of matter under strong gravity.

a strong X-ray photon density field, more Fe I atoms can be ionized.

3. The Present

3.1. Detection of relativistic Fe K and Fe L lines in the active galaxy 1H 0707-495

The behavior of matter accreted by the black hole is of considerable interest due to the intense radiative power released. This matter releases the energy as radiation which then back-illuminates the matter, giving rise to a reflection spectrum rich in emission lines (Ross and Fabian 1993, Miniutti et al. 2003, Fabian et al. 2004). Relativistic Fe K **and** Fe L lines have been first detected in the NLS1 1H 0707-495 (Fabian et al. 2009, c.f. Fig. 2). Relativistic distortions of the line make them sensitive to the strong gravity and spin of the black hole. The accompanying iron L-line emission should be detectable when the iron abundance is high (about 10 times Solar with the other elements at Solar values). A dense nuclear star cluster has most probably led to the formation of massive white dwarf binaries which enriched the nucleus with SN Ia ejecta rich in iron. The normalization of the Fe K and Fe L lines in photon spectra are in the ratio 20 to 1, in agreement to atomic physics.

The bright iron L emission allows the detection of a reverberation lag of about 30s between the direct X-ray continuum and its reflection from matter falling into the black hole (Fig. 3). The observed reverberation timescale is comparable to the light-crossing time of the

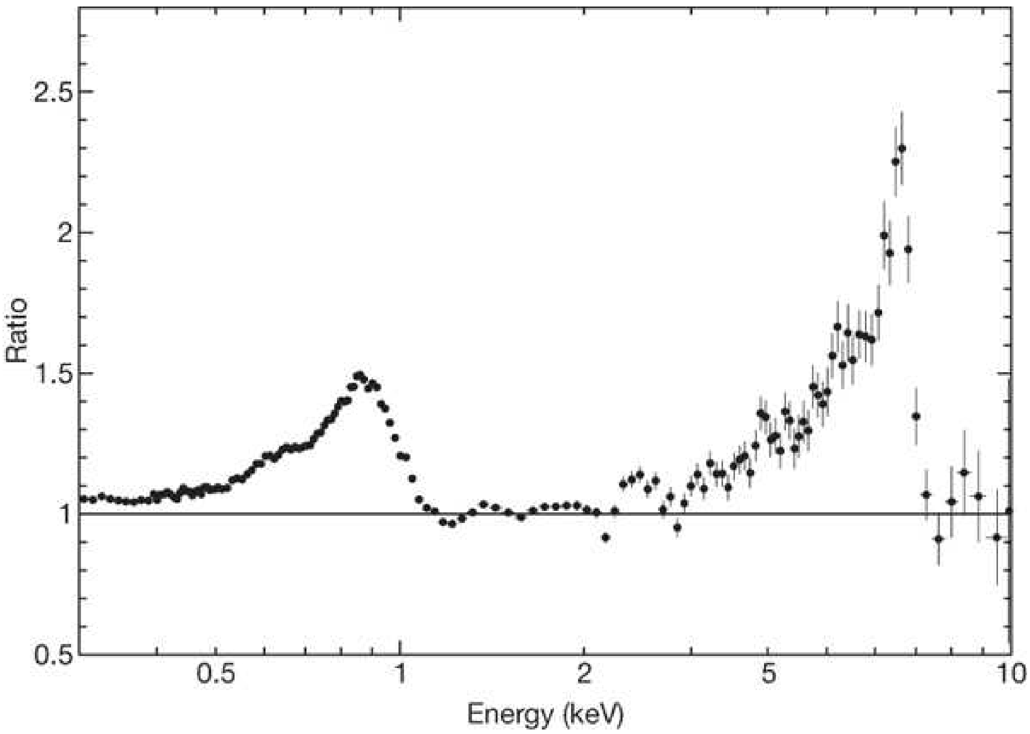

Fig. 2. The first detection of both Fe K and Fe L line emission in the NLS1 1H 0707-495 (Fabian et al. 2009). The ratio of the normalization of the Fe K to the Fe L line in photon flux is 20 to 1, in agreement to atomic physics. The Fe L line becomes most probably detectable due to the high Fe abundance which is about 9 times solar.

innermost radii around a supermassive black hole. At the shortest frequencies positive lags are detected, i.e. the soft band (0.3-1.0 keV) comes first and is followed by the hard band (1.0-4.0 keV). The key interpretation is that slower variations, lower frequencies in the frequency depended time lags plot come from larger radii where there may be significant viscous time delays as accretion rate variations propagate in. On time scales smaller than 30 minutes negative lags are detected with a maximum of 30 seconds. These negative lags are the opposite sense to a inverse Comptonization lag produced by upscattering of photons and is explained by reverberation.

3.2. NLS1 Science

In this Section I concentrate on the accretion-rate dependence on black hole masses in LINER galaxies, broad-line Seyfert 1 galaxies and NLS1s. Fig. 4 shows the relevant results. While LINER galaxies accrete a very low rates of their Eddington accretion rates (Balestra 2008), with values ranging from about $10^{-6..-2}$, the accretion rate is increasing with decreasing masses of the black hole. Kollmeier (2006) have investigated 536 broad-line Seyfert 1 galaxies and find a relatively narrow scatter in the Eddington accretion rates of about 0.1. The range of black hole masses covered are between about $10^{7..9}$ solar masses. NLS1s exhibit the lowest black hole masses and the highest accretion rates (Tanaka et al. 2005). The most probable explanation for the trend shown in Fig. 4 is that NLS1s are AGNs just in the forming (Mathur 2000) with low black hole masses and still a lot of gas reservoir to feed the black hole. In addition, intense starforming processes are expected which yield to the

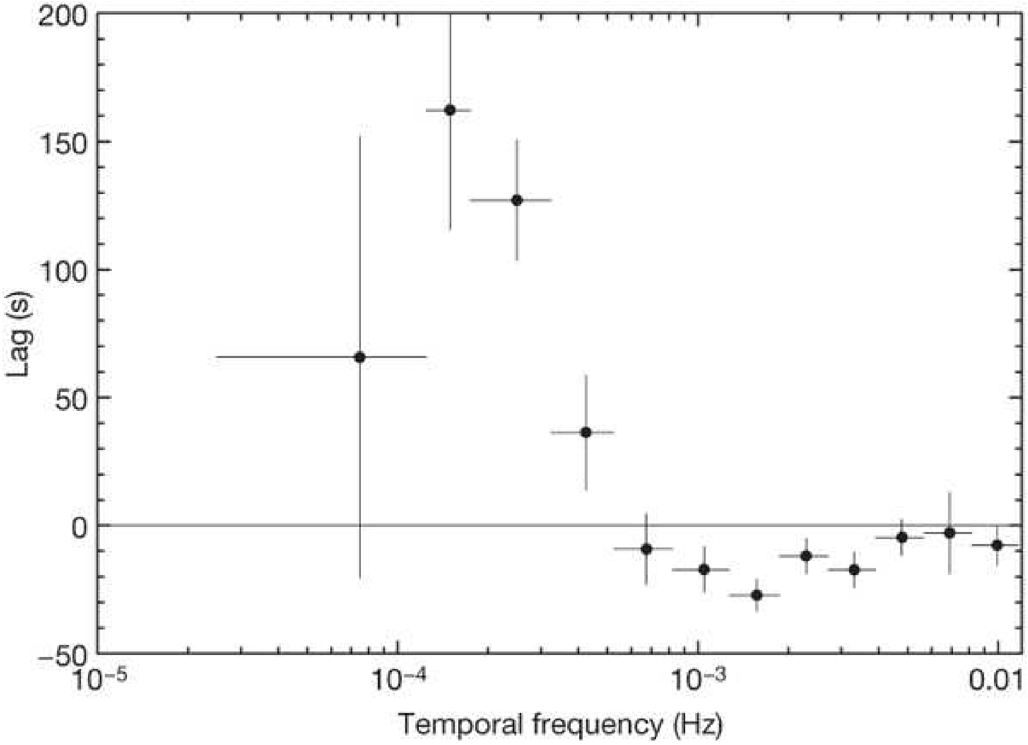

Fig. 3. Frequency dependent time lag of 1H 0707-495 (adopted from Fabian et al. 2009). The soft band is defined in the energy range between 0.3 and 1.0 keV, the hard band between 1.0 and 4.0 keV. A positive time lag indicates that the hard band follows the soft band, opposite to negative time lags. At the lowest frequencies positive time lags are detected. These are interpreted as accretion rate fluctuations at larger distances to the black hole. A significant negative time lag lag has been detected at 30 seconds. This is interpreted as the detection of a reverberation lag.

enrichment of the circumnuclear material with metals. This is supported by the Fe overabundance in the NLS1 1H 0707-495 as described by Fabian et al. (2009) or Boller (2003) in IRAS 13224-3809. Broad-line Seyfert 1 galaxies have higher masses of their black holes and most of the surrounding gas has already accreted by the black hole resulting into lower values of their Eddington ratios. The low accretion rate values in LINERs are most probably due advection-like accretion flow modes.

The black hole growth due to accretion result in other changes in the observational parameters of AGNs. The FWHM of the permitted lines from the BLR will increase with time as the FWHM value is correlated with the black hole mass and it is inversely correlated with the accretion rate. An increasing black hole mass will result into a lower ionizing continuum as the Planck spectrum of the accretion disk photons is shifted out of the observed X-ray band. This will also result into flatter soft and hard photon indices. The details of these effects are described in Boller (2005).

4. The Future

The expected launch of future X-ray missions like eROSITA, ASTRO-H or the LISA experiment, the successful launch of the Planck- and Herschel satellites, the expected new generation of extremely large optical telescopes might have an important impact on understanding the physics of the multifrequency behavior of cosmic sources. Some science aspects which

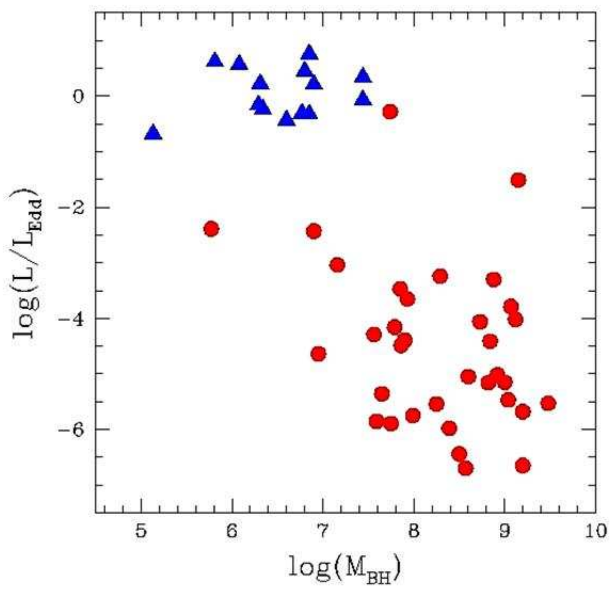

Fig. 4. Accretion rate as a function of the black hole mass (Balestra 2008, Kollmeier 2006, Tanaka et al. 2005) which appear to be anticorrelated. The highest accretion rates are detected in NLS1s, where values between about 10 to 20 times above the Eddington ratio are observed.

might be explored with much larger precision as listed in the 'IXO white papers' are:

i) the study of matter under extreme conditions, the evolution of supermassive black holes, the study of matter orbiting black holes or solving the equation of state in neutron stars;
ii) the study of galaxy formation and cosmic feedback or the search for the missing baryons;
iii) what are the life cycles of matter and energy, how do supernovae explode and how are the iron group elements created, how do high-energy processes affect the planetary formation or how are particles accelerated in the universe;
iv) understanding the nature of Dark Matter and Dark Energy, gravitational wave physics and an improved synergy between astroparticle physics and observations.

5. DISCUSSION

WOLFGANG KUNDT: When you speak about relativistic spectral lines, what are the widths of their red and blue wings?

THOMAS BOLLER: The width of the red wing of the Fe K line in 1H 0707-495 is about 4 keV. The blue wing is much sharper with a value of about 600 eV, in agreement with the prediction from the special and general relativity.

ANDRZEJ ZDZIARSKI: Why are negative time lags are not seen in other AGNs?

THOMAS BOLLER: Negative time lags have been detected in Ark 564. However, the time lag is only 11 ± 4 seconds and less significant compared to the negative time lag as detected in 1H 0707-495 (Fabian et al. 2009). I expect the detection of other negative time lags in AGNs when they have long X-ray exposures and significant X-ray variability according to the prediction from the light bending model (Miniutti et al. 2003).

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