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XMM-NEWTON SCIENTIFIC HIGHLIGHTS: X-RAY SPECTROSCOPIC POPULATION STUDIES OF AGN

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Abstract. In this paper I review the contribution that the XMM-Newton ESA X-ray mission has given to our understanding of Active Galactic Nuclei, together with other operational, and complementary, X-ray facilities. I will focus on answering three basic questions: a) to which extent do AGN share the same engine?; b) to which extent are AGN "relativistic machines"?; c) to which extent do AGN affect their immediate environment?

Keywords: X-rays: galaxies, X-rays: general, galaxies: active.

1. Goals of this paper

After more than 10 years of successful scientific operations, XMM-Newton has provided the scientific community with a rich harvest of data in all fields of astrophysical investigation. The nature of Active Galactic Nuclei (AGN) is the most productive field of investigation based on XMM-Newton data in terms of number of published papers in refereed journals (Guainazzi [26], to which readers are referred for a short description of the XMM-Newton scientific payload and performances). We have achieved significant progress in our understanding of how accretion onto super-massive black holes (SMBHs) works, on the similarity of the "central engines" among different classes of observationally distinct AGN, and on the interaction between the AGN and the surrounding gas and dust.

In this paper, I will review how XMM-Newton has contributed to this progress. I will concentrate on *spectroscopic* studies of sizable samples (number of objects ≥ 25) of nearby ($z \leq 0.1$) radio-quiet AGN. Due tribute will be paid, whenever relevant, to the contribution by other, and largely complementary, X-ray facilities which have been successfully operating alongside XMM-Newton, such as *Chandra*, INTEGRAL, and *Swift*.

2. To which extent do AGN share the same engine?

AGN exhibit a very diverse phenomenology. One of the basic observational classifications of radio-quiet AGN is based on their optical spectrum. Emission line profiles in "Broad-line" (or "Type 1") AGN have widths $\gtrsim 1000\,\mathrm{km\,s^{-1}}$; by contrast, the optical spectra of "narrow-line" ("Type 2") AGN exhibit narrower ($\lesssim 1000\,\mathrm{km\,s^{-1}}$) profiles, primarily from forbidden transitions. However, this observational diversity hides a more fundamental identity: a recent study of 165 Seyfert galaxies (the most common class of nearby radio-quiet AGN) in the INTEGRAL/IBIS catalogue [61] shows that the average intrinsic spectral shape of Type 1 and Type 2 objects is statistically indistinguishable above 15 keV. The distributions of the α_{ox} parameter (the logarithm of the flux density ratio between X-ray and 5500 Å) are very similar in Type 1 and Type 2, once the X-ray flux density is calculated at 20 keV [7].

Why does one need high-energy measurements to discover this hidden identity? Because the spectra of radio-quiet AGN are significantly affected by obscuration due to intervening gas and dust along the line of sight. Even over the two decades in energy between 0.1 and 10 keV (where most, and the most sensitive, X-ray spectroscopic measurements of AGN are currently available), the observational appearance of Type 1 and Type 2 AGN is remarkably different. The latter are characterized by neutral gas photoelectric absorption column densities $\geq 10^{22}\,\mathrm{cm^{-2}}$ (this fact has been known since the dawn of AGN high-energy astrophysics; [4, 75], cf. [72] for an analysis of the most carefully selected sample of Seyfert galaxies to date). This feature is almost entirely absent in Type 1 objects.

This observational fact lends support to the so called "unification scenario", originally postulated by Antonucci & Miller [2] to explain the appearance of broad lines in spectropolarimetric observations of "narrow-line" AGN. The 0-th order formulation of this scenario (see [1] for a review) posits an azimuthally-symmetric gas and dust structure surrounding the AGN. This structure (traditionally referred to as the "torus") impedes the view of the central engine as well as of the Broad Line Regions (BLRs), i.e. the gas clouds responsible for the production of broad optical lines, if the line-of-sight to the AGN intercepts it. In the simplest interpretation of the Unified scenario, the torus is a pc-scale compact structure. The most recent observational and theoretical developments suggest rather that the torus is clumpy, extending on scales from a fraction to tens of parsecs [19, 46], and that gas in the BLR also contributes to the line-of-sight obscuration (see [11] for a review). Notwithstanding the detailed structure of the obscuring matter, X-ray surveys confirm the basic predictions of the unified scenario at a very high level of accuracy. Only 3 % of Type 1 AGN are X-ray obscured, and 3 % of Type 2 AGN are X-ray unobscured in the XMM-Newton Wide Area Survey (486 objects; [41]). The former group of exceptions can be easily explained by assuming that the host galaxy contributes to the X-ray obscuration along some line-of-sight, or by anisotropy of the AGN emission. More intriguingly, the latter class could be living proof of an elusive class of "bare" Type 2 AGN, where the BLR is missing rather than obscured. This class of objects could demonstrate that a minimum accretion rate is required for the torus and/or the BLR to form [20, 47, 49]. This hypothesis has only recently received observational support from a dedicated XMM-Newton experiment [40]. It goes without saying that one cannot rule out that the original optical classification of these outliers is simply wrong.

3. To which extent are AGN relativistic machines?

There is nowadays almost unanimous consensus that AGN are powered by accretion onto SMBHs, following the hypothesis originally formulated by Lynden-Bell [38]. In this picture, high-energy radiation comes from the innermost regions of the accretion flow, a few to tens of gravitational radii from the event horizon, due to the steep increase of the disk dissipation [60, and references therein], and due to the disk temperature profile in a Shakura-Sunyaev accretion disk [55, 69]. More recently, quasar micro-lensing [14] and X-ray occultation experiments [62, 63] have unambiguously demonstrated that the size of the X-ray source is $\lesssim 10$ gravitational radii, in agreement with early suggestions based on short time-scale X-ray variability [6].

An X-ray illuminated accretion disk extending down to the innermost circular stable orbit should Compton-scatter the primary radiation. Models of "disk reflection" have been developed since the early 1990s [23, 64] following the discovery of spectral features expected from disk reflection such as the Compton "hump" and iron fluorescent lines [45, 53]. Besides Newtonian dynamical effects, the profile of disk emission lines is distorted by special and general relativity [21, 42]. They depend on the emissivity profile along the disk, on the exact location and size of the line emitting region, on the disk inclination $\imath$ with respect to the line-of-sight, and on the black hole spin.

Recently, several studies have tried to validate our standard picture of the innermost accretion flow by looking at spectroscopic signatures of "line profile relativistic broadening" [9, 16, 44]. The results of these studies are summarised in Fig. 1.

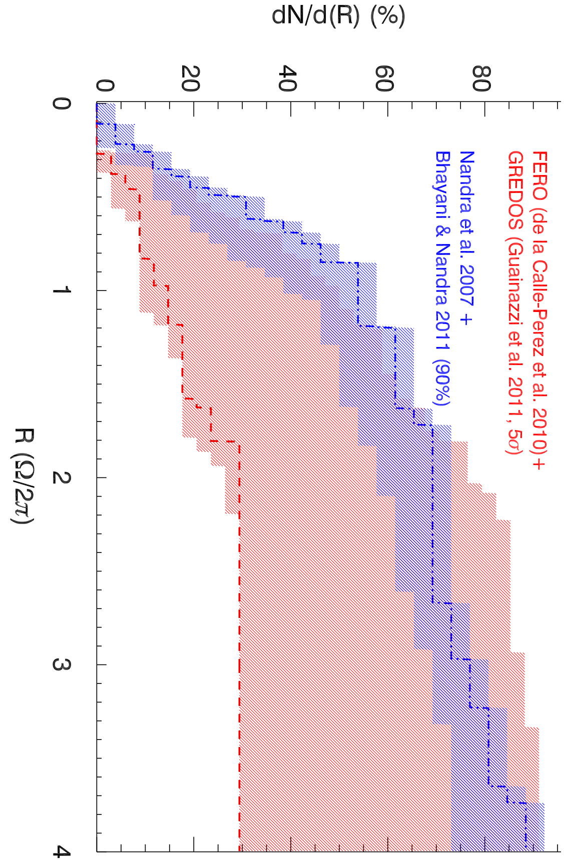

Figure 1. Cumulative distribution function of the fraction of AGN exhibiting relativistically broadened Fe K_α lines in two different samples: FERO+GREDOS (*red*; [16, 29]), and the "Nandra et al." sample (*blue*; [9, 44]). The *filled surfaces* correspond to different statistical criteria for the detection of broadened profiles: 5σ in the former, 90 % confidence level for one interesting parameter in the latter studies. The distribution functions are calculated against the "disk reflection parameter" R [39], which is proportional to the accretion disk solid angle, as seen from a point-like isotropic X-ray source. $R \equiv 1$ for a plane-parallel, infinite slab when the relativistic light bending is negligible.

They are consistent with $\simeq 90$ % of nearby Seyfert galaxies in well-defined flux-limited samples to exhibit relativistically broadened profiles. The main systematic uncertainties on these results are due to the uneven statistical quality of the data [28], as well as (and more importantly) on pending ambiguities in the spectral deconvolution of CCD-resolution X-ray spectra, even with the highest statistical quality (see [74] for a review of these issue; they propose an alternative scenario which does *not* require any relativistic effect).

In Fig. 1 the cumulative distributions are plotted against the "disk reflection" parameter R, which is proportional to the solid angle that the accretion disk covers, as seen from the – supposedly point-like – X-ray source. With the definition used in Fig. 1, $R = 1$ if the disk is a plane-parallel slab and the X-ray source is isotropic. This should be the most common geom-

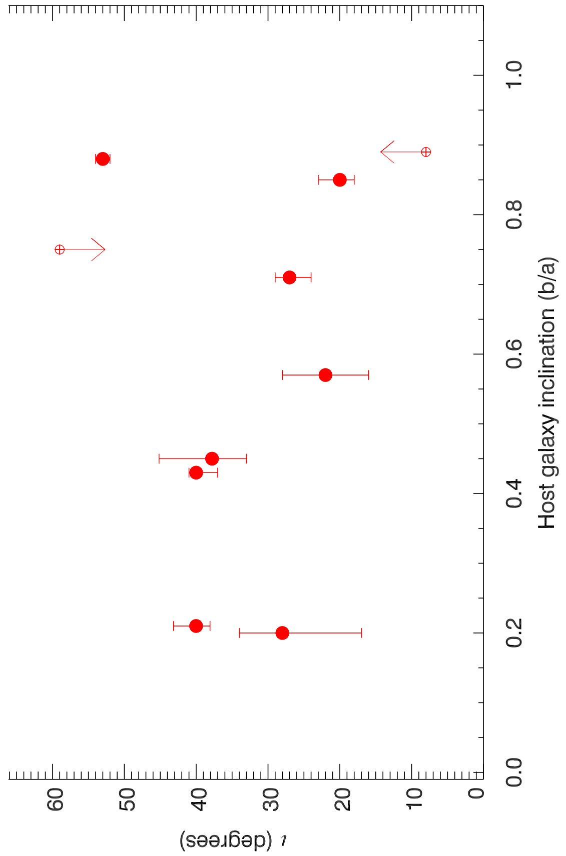

Figure 2. Accretion disk inclination angle $\imath$ derived from X-ray relativistic spectroscopy on the FERO and GREDOS samples [29] against the host galaxy inclination.

etry. However, the cumulative distribution function also increases steeply for $R < 1$, and keeps growing for $R > 1$. This evidence requires modifications of the standard picture. These issues are discussed in [29, 44]. High values of R may indicate objects where relativistic "light bending" is important, increasing the relative strength of the reflected emission when the X-ray source is located at few gravitational radii above the disk [43]. We observe that in this scenario R can be significantly larger even than 2 (the value corresponding to a reflecting slab covering a solid angle equal to 4π), because light bending increases the relative fraction of primary photons bent towards the accretion disk while *at the same time* decreasing the fraction of primary photons directly reaching the observer. When the relativistic light bending is strong, the observed ratio between the reflected and the primary fluxes is therefore unrelated to the true geometry of the reflector. However, low values of R may be indicative of a relativistic aberration in a mildly outflowing corona [8].

X-ray relativistic spectroscopy is one of the few direct ways to measure the inclination of the innermost disk region, down to a few gravitational radii from the BH event horizon. In Fig. 2 we compare $\imath$ against the inclination of the host galaxy.

There is no correlation between the two quantities. Naively, one might expect that the accretion disk preserves the host galaxy orientation due to the conservation of the overall angular momentum. Figure 2 confirms previous indications that the distribution of the angle between the radio jet and the host galaxy disk is consistent with being random [34, 67]. Galaxy-galaxy merging, or precession and warping of the innermost accretion disk due to the Bardeen & Petterson effect [5, 13] have been invoked to explain this lack of correlation.

Realistic accretion disk models predict strong emission in the soft X-ray band (below 2 keV) due to the combination of low opacity and emission lines [64]. "Soft excesses" are indeed commonly found in the X-ray spectra of AGN and quasars [50, and references therein]. A possible explanation in terms of relativistically smeared high-density outflows [24] has recently been ruled out [68]. However, reflection from an ionized disk fits well the observed XMM-Newton EPIC (Strüder et al. 2001, Turner et al. 2001) spectra [15]. A systematic study of the physical nature of soft excesses which takes explicitly into account the time-dimension (soft X-ray emission in AGN is variable on all range of timescales from hours to years) is, unfortunately, still missing.

4. To which extent do AGN affect their environment?

Disk line-driven winds are a natural prediction of relativistic accretion disk models [18, 32, 56, 57, 68, 70, 71]. Spectroscopic studies of samples of bright Seyfert galaxies with ASCA unveiled that at least 50 % of nearby bright Seyferts exhibit absorption features, which can be associated with ionized gas. Blustin et al. [12] published a systematic compilation of literature results based on data of the Reflection Grating Spectrometer on board XMM-Newton [17]. These "warm absorbers" have typical ionization parameters[1] $\xi \sim 100\,\mathrm{erg\,cm\,s^{-1}}$, column densities[2] $N_H \sim 10^{21\div22}\,\mathrm{cm^{-2}}$, and outflow velocities $\leq 1000\,\mathrm{km\,s^{-1}}$. The covering fraction, as derived from the fraction of "warm absorbed" AGN in well-defined samples, is possibly larger than 80 % [76]. More recently [54, 59], a population of high-density ($N_H \sim 10^{23\div24}\,\mathrm{cm^{-2}}$), highly ionized ($\xi \geq 1000\,\mathrm{erg\,cm\,s^{-1}}$), high-velocity ($\gtrsim 0.1c$) outflows has been discovered in XMM-Newton CCD spectra of more luminous quasars. Evidence for these more massive counterparts of historical "warm absorbers"

[1] $\xi \equiv L/(nR^2)$, where L is the ionizing luminosity, n is the electron density and R the distance between the ionizing source and the inner side of the ionized cloud

[2] To clarify an often confusing issue for a non-expert: we refer here to the column density of ionized absorbers as opposed to the photoelectric absorption from a neutral gas discussed in Sect. 2. AGN exhibiting "warm absorbers" are typically "Type 1", i.e. X-ray *un*obscured in the sense described in Sect. 2. I apologize on behalf of the AGN community for this confusing nomenclature.

has been found in $40 \div 60\,\%$ AGN in the local Universe [73].

Ionized outflows are important because they are a fundamental ingredient of our AGN structure model, and also because they provide us with a complementary view of the accretion flow. They may be tracing AGN feedback onto the surrounding gas. In order to quantitatively assess the mass rate and kinetic energy carried by these outflows, one needs to know their location or launch radius. Photoionization models yield only the product between the gas density and its distance from the ionizing continuum. An independent estimate of the density can be derived when the X-ray continuum is variable (the ionization and recombination times depend on n^{-1}; [35, 48], if meta-stable transitions are detected [3, 22], through density diagnostics on He-like *emission* line triplets ([52]; it must be assumed in this case that absorption and emission occur in the same system), or if the gas is heated by free-free absorption [65]. Blustin et al. [12] estimate upper and lower limits on the launch radius using the escape velocity, and imposing that the width of the absorbing slab is much smaller than R, respectively (otherwise stated, that the electron number density for a given ionization parameter falls rapidly with R; see [37] for a criticism to this approach). Under these assumptions, warm absorbers should be launched at parsec scale, probably via radiation pressure on gas clouds detached from the rim of the torus, and the outflow rate is of the same order as the accretion rate, with huge uncertainties. Unfortunately, different methods for estimating R give widely different results when applied to the same data [36]. Notwithstanding these uncertainties, some general conclusions can be drawn:

- At least the most powerful AGN, and maybe even more prosaic Seyferts, could release to the Interstellar Medium $10^8\,M_\odot$ of hot gas in bulges across their lifetime.
- Standard Seyferts could release enough energy to heat the ISM gas to temperatures $\simeq 10^7$ K.
- Powerful quasars ($\geq 10^{44}\,\mathrm{erg\,s^{-1}}$) could release more than the binding energy of a $10^{11} M_\odot$ bulge with dispersion velocity $\sigma \sim 300\,\mathrm{km\,s^{-1}}$, or the energy necessary to control the evolution of the host galaxy and the surrounding Intergalactic Medium.

Readers interested in a more detailed discussion of this subject are referred to [31, 66] or [30]. The last authors propose a "two-stage" feedback process, whereby a disk wind drives a weak wind or outflow in the hot, diffuse interstellar medium. This latter component is able to drive cold gas clouds in a direction perpendicular to the incident flow. This mechanism could reduce by a factor ~ 10 the energy requirement for feedback to affect the host galaxy and quench star formation (see also [58]).

On larger scales, these outflows probably connect with X-ray emitting diffuse structures, extended on

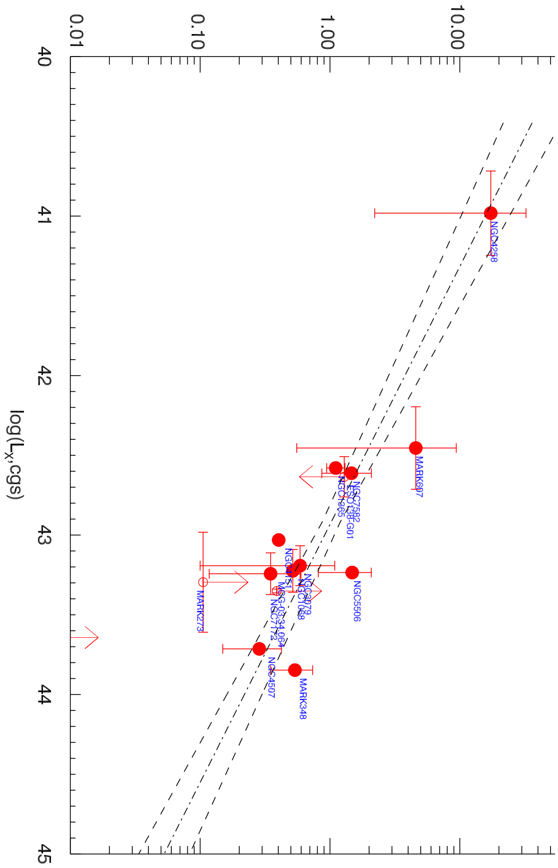

Figure 3. Ratio between the Oviii Ly-α and the forbidden component of the Ovii as a function of the X-ray luminosity in the $14 \div 195$ keV band for the Type 2 AGN of the CIELO sample [27]. The inverse of the quantity on the y-axis is an indicator of photoionization. The luminosity of Compton-thick AGN ($N_H > \sigma_t^{-1} = 1.6\times10^{24}\,\mathrm{cm^{-2}}$) was adjusted by a factor of 30. The *dot-dashed line* indicates the best fit, the *dashed lines* indicate the envelope corresponding to the 1σ uncertainties on the best-fit parameters.

scales as large as a hundred parsecs (Extended X-ray Narrow-Line Regions, EXNLRs; [10]). A systematic spectroscopic study of a sample of over 90 Type 2 AGN observed by the XMM-Newton/RGS unveiled that the gas is photoionized with a small or negligible contribution from nuclear starburst or shocked plasma ([27]; see [33] for a detailed description of the underlying astrophysics). The photoionization diagnostics are proportional to the hard X-ray luminosity, suggesting that the AGN is the ultimate ionizing power of the EXNLRs (Fig. 3).

5. A final comment

I would like to conclude this brief review with a comment. While many physical insights can be obtained from the detailed study of a few "archetypal" individual AGN, only the global view provided by a large sample of good quality spectroscopic measurements will allow us to make robust progress in our understanding of the astrophysics of such complex systems.

Spectroscopy is still the only available tool to investigate astrophysical complexity on spatial scales, which will remain unresolved for many generations to come. With the main X-ray spectroscopic missions (*Chandra*, *Suzaku*, and XMM-Newton) in their full operational maturity, enough observing time should be allocated to sizable, well-defined, complete samples of AGN. Complete, homogeneous sample coverage in the science archives over the largest possible parameter space is an obligation towards the coming generations of high-energy astronomers, should this class of researcher still exist in the future (cf. Ubertini, this volume).

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Discussion

Maurice van Putten — Could you comment on the detection of Quasi Period Oscillations (QPOs) in AGN?

Matteo Guainazzi — The only positive detection of a ~ 1 hour QPO in AGN was reported by Gierliński et al. (2008) in REJ1034+396. A recent systematic analysis of over 160 bright AGN observed by XMM-Newton has not discovered any further QPO (Ponti et al. 2012).