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Cosmological Evolution of the Central Engine in High-Luminosity, High-Accretion Rate AGN

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Abstract

In this paper I discuss the status of observational studies aiming at probing the cosmological evolution of the central engine in high-luminosity, high-accretion rate Active Galactic Nuclei (AGN). X-ray spectroscopic surveys, supported by extensive multi-wavelength coverage, indicate a remarkable invariance of the accretion disk plus corona system, and of their coupling up to redshifts $z \simeq 6$. Furthermore, hard X-ray ($E \gtrsim$10 keV) surveys show that nearby Seyfert Galaxies share the same central engine notwithstanding their optical classification. These results suggest that the high-luminosity, high accretion rate quasar phase of AGN evolution is homogeneous over cosmological times.

Keywords: Active Galactic Nuclei.

1 Outline

Thanks to its leap in sensitivity by over two orders of magnitude, the Medium Sensitivity Survey carried out by the *Einstein* observatory (EMSS, Maccacaro et al. 1981) collected for the first a statistically sizable sample of extragalactic X-ray sources. Studying a sample of 190 extragalactic sources, Giovannelli & Polcaro (1986) concluded that the observed linear relation between X-ray luminosity and redshift over several orders of magnitude made evident a physical continuity between the different classes of extragalactic X-ray objects.

The sample in Giovannelli & Polcaro (1986) was a "mixed bag" of different objects: Active Galactic Nuclei (AGN), elliptical/S0 galaxies, and spiral/irregular galaxies. While it is now accepted that most of the X-ray emission in inactive galaxies is due to a combination of diffuse Inter-Stellar Medium, halos, and X-ray binaries (see Fabbiano 1989 for an early review), there is almost undisputed consensus that the formidable energy output emerging from AGN is due to accretion onto super-massive black holes (see, however, the contribution by prof. Kundt for a different view). Sub-arc-second resolution imaging with *Chandra*, as well as the unprecedented XMM-Newton throughput have made possible a detailed characterisation of the high-energy Spectral Energy Distribution (SED) in large samples of AGN, covering a range in luminosity of almost ten orders of magnitudes, and cosmological distances well beyond the peak of the nuclear activity (Brandt & Hasinger 2005, Elvis et al. 2012, Pounds 2013).

Time is ripe to address some fundamental questions on the nature of accretion onto super-massive black holes, that the small size of the EMSS extragalactic sample left open. In this contribution I will focus on two of them:

- do AGN share the same engine *at all cosmological times*?
- do AGN share the same engine?

The answer for *all types of AGN* at *all accretion rates* would be clearly: "they don't". However, similarities in the observational properties of specific sub-classes of AGN allow us to give these question astrophysically useful positive answers, at least as far as the members of these sub-classes are concerned. In this review I deal with mainstream *radio-quiet*[1], high-Eddington ratio ($\dot{m}/\dot{m_{Edd}} \gtrsim 10^{-2}$)[2] AGN. I assume hereby the traditional wisdom separation in bolometric luminosity between Seyfert Galaxies ($L < 10^{44}$ erg s^{-1}) and Quasars (QSO), whenever relevant. The contribution by M.Elitzur to these proceedings discusses a central engine unification scheme encompassing also low-luminosity, low-accretion rate systems.

[1] In this paper, I assume a qualitative definition of *radio-quiet* (as opposed to *radio-loud*) AGN as those where the contribution of relativistic jets to the optical-to-X-ray Spectral Energy Distribution is negligible. Quantitative definitions of AGN radio-loudness were introduced by Kellermann et al. (1989), Miller et al. (1990), and Panessa et al. (2007), among others.

[2] We define the mass accretion rate in units of Eddington as: $\dot{m} \equiv \eta L_{Edd}/c^2$, where $L_{Edd} \equiv 4\pi G M_{BH} m_p c$, M_{BH} is the black hole mass, m_p is the proton mass, c is the speed of light, and $\eta \simeq 0.1$ is the efficiency of gravitational losses into radiation conversion.

2 Cosmological Evolution of the AGN Central Engine

2.1 Direct observables

AGN are multi-wavelength machines. They emit comparable power per decade frequency from the IR to the γ-ray band (Elvis et al. 1994). More importantly for the astrophysical study of accreting super-massive black holes, the bulk of the radiation emitted in each rest-frame energy band carries information on a specific astrophysical process occurring in the nuclear region. UV and X-rays are the most appropriate bands to study spectroscopically the sub-pc scale around accreting massive black holes.

In AGN accreting at a rate $\dot{m} \gtrsim 10^{-2}$ the Eddington value the UV emission is dominated by a "blue bump", believed to be due to thermal emission from the accretion disk (Czerny & Elvis 1987). The high-energy band is dominated by Comptonisation of disk photons by a $\sim 10^2$ keV temperature corona (Zdziarski et al. 1995, Perola et al. 2002) with a largely unknown geometry. Haardt & Maraschi (1991) proposed a "sandwich" geometry embracing the accretion disk. Compact coronal geometries have recently experienced a revival following the possible discovery of relativistic light bending (Miniutti & Fabian 2004) and disk reverberation (Fabian et al. 2009) in X-ray observations of nearby Seyfert galaxies.

UV and X-rays are therefore the natural energy bands where to look for any cosmological evolution of the central engine in luminous AGN. In practical terms, metrics accessible to CCD-resolution AGN spectra are the intrinsic shape of the X-ray spectrum, parametrised through the photon index Γ, which yields information on the corona; and the UV to X-ray flux ratio, parametrised through the $\alpha_{ox} \propto \log(L_{2keV}/L_{2500\AA})$ (Tananbaum et al. 1979), which yields information on the disk-corona coupling. For unsaturated Comptonisation of non relativistic thermal distributions of electrons, $\Gamma \propto y^{-1/2}$, where the Comptonisation parameter $y \propto kT \times Max(\tau_{es}, \tau_{es}^2)$, kT is the electron temperature and τ_{es} the optical depth for electron scattering (Rybicki & Lightman 1979). The measurements of the spectral exponential cut-off at energies $E \sim kT$ would provide a full characterisation of the physical properties of the corona. However, such measurements are accessible only for a handful of X-ray bright nearby AGN even in the NuSTAR (Harrison et al. 2013) era. Other observables probe in principle the innermost regions of the accretion flow, such as the ubiquitous, and black hole mass dependent, X-ray variability (Mc Hardy et al. 2006, Ponti et al. 2012) and the relativistic distortion of X-ray emission lines produced in a X-ray illuminated accretion disk within a few gravitational radii from the innermost circular stable orbit (Fabian et al. 1989). These effects are, however, also difficult to measure at high redshift.

Fig. 1 shows a qualitative scheme of the intrinsic AGN UV-to-X-ray SED for reference.

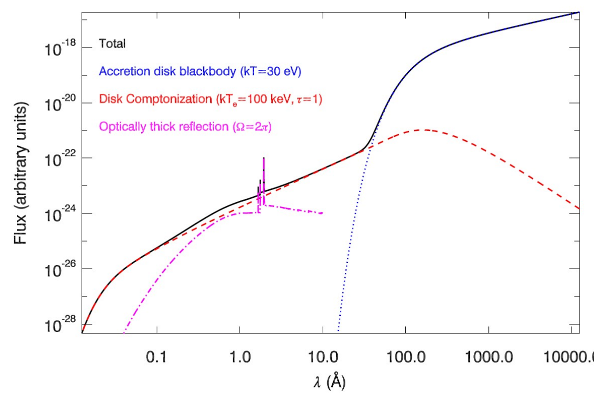

Figure 1: Schematic view of an AGN intrinsic UV-to-X-ray spectrum. *Blue*: thermal emission from a luminous accretion disk with a temperature at the innermost radius of 30 eV; *red*: unsaturated Comptonisation of soft disk photons with kT_e=100 keV and τ_{es}=1; *magenta*: reflection from a plane-parallel infinite slab of cold ($\sim 10^4$K) matter (Compton continuum plus Fe and Nickel K_α and K_β fluorescent emission lines; after Nandra et al. 2007)

Sizable samples of X-ray selected AGN up to redshift $\simeq$6 have been collected by difference catalogues and surveys: CHAMP (Green et al. 2012), Chandra Deep Fields (Steffen et al. 2006), 2XMM (Watson et al. 2009, Young et al. 2009), COSMOS (Elvis et al. 2012, Lanzuisi et al. 2013). They agree in finding no evidence for cosmological evolution of either Γ or α_{ox}. Similar results were obtained by specific observational programs targeting the farthest X-ray selected QSO (Vignali et al. 2005). The constrains on α_{ox} are particularly tight: once its dependency on the luminosity is corrected for, the average of the α_{ox} distributions in different redshift bins agree within $\pm$0.1 (Steffen et al. 2006). Taken as a whole, these results indicate a remarkable invariance of the corona-disk coupling over 90% of the look-back time.

2.2 Indirect observables

Other observables can be used to probe indirectly the nuclear SED: we focus in this Section on emission lines in the optical, and in the X-ray band.

Optical spectroscopy probes the physical condition of gas on a variety of different scales in the nuclear environment: from the *Broad Line Regions* (BLRs) clouds, emitting lines primarily from permitted transitions with widths $\gtrsim$2000 km s^{-1}, to the *Narrow Line Regions*

(NLRs), emitting lines primarily from forbidden transitions with widths $\lesssim$1000 km s^{-1}. These gaseous systems cover the whole range of distances from the central engine between light-days (Peterson et al. 2004) to tens-hundreds of kpc (Pogge 1988, 1989a, 1989b). Extended NLRs are also copious sources of X-rays (Young et al. 2001, Bianchi et al. 2006). Gas in these regions is photo-ionised by the AGN. Photo-ionisation models applied to the observed spectra allows one to reconstruct the ionising SED, and even - in a few cases - the past history of the accreting black hole (Dadina et al. 2010).

The farthest optically identified AGN is ULASJ1120+0641 at $z = 7.085$, a $M_{BH} = 2 \times 10^9 M_\odot$ quasar (QSO). Its optical spectrum is almost indistinguishable from composite spectra of AGN at lower redshift (Mortock et al. 2011). Studies of QSO optical spectra at $z \geq 5$ indicate no evolution of the metallicity as a function of redshift (Juarez et al. 2009). These results suggest that the invariance of the central engine extends to the immediate environs of the accreting black hole up to redshifts $\simeq$7.

Due to the combination of high fluorescent yield and abundance, iron K_α fluorescent emission line is among the most common spectral features in X-ray spectra of cosmic sources. It is well isolated from transitions due to the closest elements; even at CCD resolution ($E/\Delta E$~40) one can easily resolve fluorescence emission lines from He-like, and H-like recombination lines (statistics permitting). An unresolved component of the neutral iron K_α fluorescent line has been detected almost ubiquitously in nearby AGN (Yaqoob & Padmanabhan 2004; Nandra 2006). This feature traces reprocessing of the primary nuclear emission by optically thick gas. While this feature is too weak to be detected in X-ray spectra of individual sources at high redshift, spectra stacking techniques allowed the COSMOS survey to probe its presence up to redshift $z \simeq 3$. Fitting these stacked spectra with simple phenomenological continua leaves residuals consistent with neutral iron K_α emission (and weaker residuals consistent with recombination lines from He- and H-like iron). The Equivalent Width of such features is independent of redshift (Chaudhary et al., 2010; Iwasawa et al. 2012), once corrected for the known dependence on the absorption-corrected X-ray luminosity, the so called "Iwasawa-Taniguchi" effect (Iwasawa & Taniguchi 1993; Bianchi et al. 2007). This result implies a similarity of the primary X-ray SED, as well as of the geometrical configuration and ionisation stage of the reprocessing matter at different cosmological times.

2.3 However, AGN *do* evolve ...

These results shall not be interpreted as due to the fact that the AGN population as a whole do not evolve! The AGN population evolves in density and luminosity over cosmological times (see Brandt & Hasinger 2005 for a recent review). This may in principle affect the AGN population being probed at different redshift by current surveys. Hopkins et al. (2008) and Hickox et al. (2009) present an evolutionary scenario whereby all AGN go through the same evolutionary steps. Merging or secular processes (gas instabilities) trigger simultaneously the quasar phase and the growth of the stellar bulge when a galaxy's dark matter halo reaches a critical mass $\sim 10^{12-13}$ M$_\odot$. The peak of the quasar phase accreting at high Eddington ratio, when massive black holes accrete the bulk of their mass, occurs at different redshifts depending on the mass of the primeval dark mass halo. The whole AGN evolutionary sequence would start from a cold gas-rich, rotation dominated galaxy, pass through a dust- and optically-thick gas enshrouded phase, evolve into the QSO phase, and then to a gradual decline of the AGN activity until the galaxy become a "red and dead" elliptical with intermittent radio activity. All these phases would be present in an observed AGN sample at any redshift. The QSO phase is, however, the best one to probe the conditions of the innermost regions close to the central engine.

The discovery of a $\sim 10^9$M$_\odot$ black hole at $z \sim 7$ is puzzling for models of cosmological black hole growth. It is not simple to understand how the required mass could have accreted from seed black holes at $z \geq 10$. Broadly speaking (see Volonteri 2010 for a review) models of seed black hole formation and evolution can be classified as: a) light (M_{BH} $\sim 10^{2-3}$ M$_\odot$) and rapidly accreting seeds forming at very early cosmic time (z $\simeq$20–50); b) heavy (M_{BH} $\sim 10^{4-6}$ M$_\odot$) and slowly accreting seeds forming at later stages (z $\simeq$5–10): c) intermediate seeds between the two cases above. None of these scenarios is free of potential shortcomings (Milosavljević et al. 2009; Volonteri & Begelman 2010). If massive enough ($\gtrsim 10^5$ M$_\odot$), electromagnetic signals from these early seeds could be detected by future large observatories. Otherwise the detection of gravitational waves produced when compact objects fall onto the seed could provide constraints on a population in the mass range M_{BH} $\sim 10^{4-7}$ M$_\odot$. These topics will be addressed by a future ESA's L-class X-ray mission in the framework of the Cosmic Vision program, one of whose basic science theme is: "*How did the Universe Originate and What is it Made of?*" (ESA 2005).

3 Do *Really* AGN Share the Same Engine?

So far we have *assumed* the all AGN in the quasar phase at a given time share the same central engine. X-rays provide the ideal wavelength to test this assumption for radio-quiet AGN in the local Universe. In order to understand why, we need to have a closer look at the configuration of gas and dust surrounding the AGN central engine, and on how it affects the phenomenological appearance of AGN.

In Sect. 2.2 it was shown that the ubiquitous detection of K_α fluorescent emission lines corresponding to neutral or mildly ionised iron (together with the associated continuum Compton-reflection "hump"; Nandra & Pounds 1994) is considered a clear evidence for reprocessing of the primary nuclear emission by optically thick gas in the AGN environs. The geometry of this gas structure is controversial. Traditional wisdom invoked a compact symmetrical molecular "torus" (Antonucci & Miller 1985). Its azimuthal symmetry would introduce a dependence of the AGN observational properties on the line-of-sight to the nucleus. These orientation effects would be primarily (but not exclusively; see Nicastro 2000) responsible for the properties of their optical spectra: BLRs would be visible only through lines-of-sight not intercepting the torus. For the high reddening expected when radiation passes through the torus clouds ($N_H > 10^{22}$ cm^{-2}) optical broad lines would be suppressed, and only narrow emission lines would be visible (see Antonucci 1993 for a review). In this "AGN unified scenario" Broad- and Narrow-Line AGN share the same common engine. Hoverer, early simulations (Pier & Krolik 1992) pointed out that it is difficult to prevent such a structure from gravitationally collapsing on time-scales much shorter than the typical AGN duty-cycle ($\gtrsim$1 Gyr). Recent models invoke a "clumpy" model as a solution to this issue (Nenkova et al. 2002, 2008). In this framework, the AGN classification into Broad- and Narrow-Line AGN should be reinterpreted in probabilistic terms: even AGN seen at very high inclination angles (*i.e.*, for which the traditional unified scenario would predict that they could be only Narrow-Line AGN), would have some probability of being detected as Broad-Line AGN depending on the number, size and dynamics of the torus clouds (Eliztur 2012; see also Eliztur's contribution to these proceedings for a discussion of this interpretative scenario). First direct X-ray evidence for the torus clumpiness might have been recently detected in the heavily obscured AGN Markarian 3 (Guainazzi et al. 2012).

Notwithstanding the detailed structure of the torus, and the consequently corrected interpretation of the Unified Scenario, there is a tight correlation between optical and X-ray spectroscopic properties in nearby AGN: optical "Narrow-Line" AGN exhibit X-ray spectra seen through large column densities of cold photo-electrically absorbing gas ($N_H \gtrsim 10^{22}$ cm^{-2}; Awaki et al. 1991; Risaliti 2002); optical "Broad-Line" AGN are X-ray unobscured. Exceptions to this rules are $\simeq$3% in large AGN X-ray spectroscopic surveys (Mateos et al. 2010), and can be easily explained by variability between non-simultaneous optical and X-ray observations, X-ray obscuration by matter in the host galaxy, or even classification issues in poor-quality optical spectra. One needs to carefully correct for absorption (Singh et al. 2011), or observe in energy ranges (as much as possible) unaffected by obscuration to probe the innermost region of AGN belonging to different optical classes. The latter avenue have been recently opened by the unprecedented sensitivity achieved by the INTEGRAL/IBIS and the Swift/BAT instruments above 10 keV. Sample of more than 100 nearby AGN detected above 10 keV are discussed, among others, by Beckmann et al. (2009); Ricci et al. (2011), Molina et al. (2013) for IBIS, and Burlon et al. (2012) for BAT, respectively. The distributions of Γ in samples of X-ray obscured and unobscured AGN are consistent within $\Delta\Gamma \simeq \pm 0.1$. The distributions of α_{ox} remain indistinguishable also when the X-ray luminosity density is calculated in the hard X-ray band (Beckman et al. 2009). Interestingly enough, Ricci et al. (2011) suggested that the reprocessing continuum spectra components are stronger when AGN are obscured by a column density 10^{23} cm$^{-2} \leq N_H \leq 10^{24}$ cm^{-2}. This ingredient does not belong to the 0^{th} order unified scenarios. At this level of obscuration a contribution by BLR clouds is likely (Elvis et al. 2004; Risaliti et al. 2005, 2007; Bianchi et al. 2009). While this result is a wise reminder of the intrinsic complexity of gas and dust structures responsible for orientation- (and time-)dependent obscuration of the primary continuum, it does not in itself invalidate the basic assumptions of the Unified Scenario.

4 Conclusions

In summary:

- hard X-ray spectroscopy shows that all (local) high-accretion rate AGN share the same central engine notwithstanding the optical classification
- UV and X-ray spectroscopy shows that AGN in the same phase of their evolution (the high accretion rate, unobscured "quasar phase") share the same engine up to $z \simeq 6$
- optical (BLR emission) and X-ray spectroscopy (Fe K_α fluorescent line) show that the physical properties and geometrical configuration of the circumnuclear gas in highly accreting AGN are similar in local and high redshift AGN up to $z \simeq 7$

The contribution by Dr. Moshe Elitzur to these proceedings discusses aspects of the AGN central engine unification encompassing also low-luminosity, low-accretion rate systems.

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