Winds in the AGN environment : new perspectives from high resolution X-ray spectroscopy

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English Summary

Motivation

Galaxies are giant, gravitationally bound systems containing up to 100 billions of stars. Every galaxy hosts a supermassive black hole (SMBH) in its center. Supermassive means a mass of millions-up-to-billions times the mass of the sun. In 17% of the galaxies the central SMBH is active. In these so-called Active Galactic Nuclei (AGN, a.k.a. Seyfert galaxies, or quasars), the optical luminosity of the point-like nucleus overcomes the starlight luminosity of the entire galaxy. This enormous release of radiation, which ranges from radio up to gamma-ray energies, is powered by the gravitational infalling of galactic material onto the SMBH. Gravitational accretion is indeed the most efficient way in nature to extract energy from normal matter.

Astrophysical measurements show that the mass of the central SMBH determines the number of stars contained the galactic spheroid (the so-called bulge). This is the so-called $M-\sigma$ relation that we show in Fig. 1.

Thus, somehow, while the galaxy evolves, the activity of the central SMBH influences its ability to form stars. Theoretical models for this so-called AGN feedback prescribe that a fast gaseous wind, powered by the black-hole activity, expands in the galactic environment and interacts with it in a complex way. In some conditions, the nuclear wind is able to drive a large-scale outflow which eventually depletes the galaxy of its gas reservoir. Hence, as a consequence of the lack of cold gaseous material, the galaxy stops forming stars and the black hole stops growing. This mechanism is believed to regulate $M-\sigma$ relation.

AGN winds of different kinds are observed at submillimeter, infrared, optical, UV, and X-ray energies using spectroscopical techniques. From a spectroscopical observation, the physical properties of the wind can be measured. These can be compared with the predictions of the current theoretical scenarios. The ultimate aim of this research is finding the observational proof of AGN feedback.

Anatomy of an AGN

The observational properties of AGN can be quite diverse. For instance, some AGN are powerful radio emitters, while some others are not. From a spectroscopical point of view, AGN can be divided in two classes. Type 1 AGN exhibit both narrow and broad emission lines in the optical/UV/X-ray spectrum, while the spectrum of type 2 AGN displays only narrow emission lines. We believed that this dichotomy is explained by a simple Unified Model. In Fig. 2 we show the basic AGN anatomy.

Inside out, the model comprises:

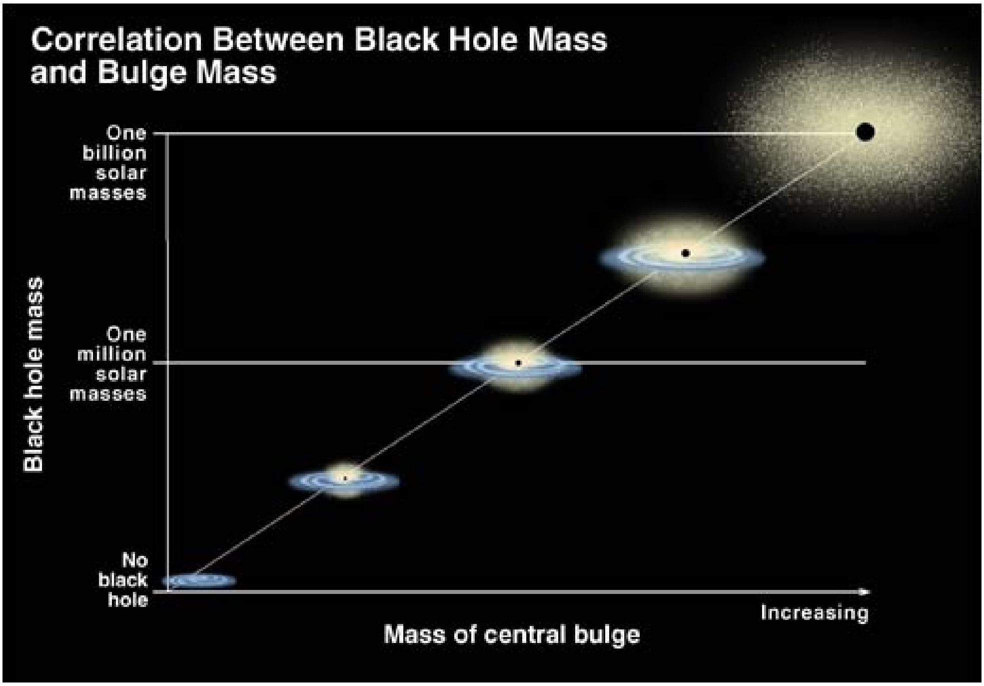

Figure 4.10: Graphical representation of the black hole mass-galaxy bulge mass correlation. [Credit: K. Cordes & S. Brown (STScI)]

1. A SMBH surrounded by an accretion disk. The disk emits thermal radiation mostly in the optical/UV band.
2. A Broad Line Region (BLR) formed by ionized gas clouds orbiting around the black hole at velocities of the order of 10 000 km s^{-1}. The BLR is located at a maximum distance of few light-days from the nucleus.
3. A torus of optically-thick, cold, material surrounding the nucleus and the BLR. The torus is located at a distance of few light-years from the nucleus.
4. A conically-shaped narrow line region (NLR) formed by ionized gas clouds orbiting around the center at velocities of the order of few 100 km s^{-1}. The NLR is located above and below the pole the torus and may extend up to distances of the order 100 light-years from the nucleus
5. A collimated jet of relativistic particles, emanating from the nucleus. The particles in the jets emit synchrotron radiation in the radio band. The jet is not always present. This determines whether the AGN is radio-loud or radio-quiet.

According to this geometry, the torus screens the nucleus and the BLR light along the equatorial direction. Thus, AGN viewed from a polar inclination angle are not obscured

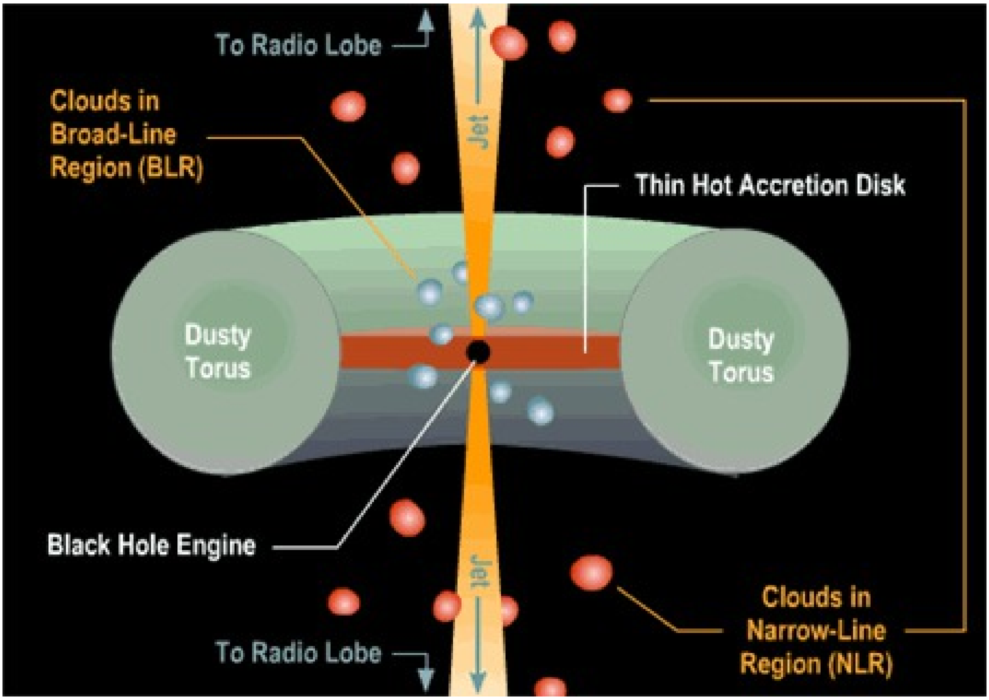

Figure 4.11: Schematic representation of the basic anatomy of an AGN, according to the so-called "Unified Model". [Credit: Brooks/Cole Thomson Learning]

by the torus and will appear as type 1. Conversely, AGN viewed from an equatorial line of sight will appear as type 2.

AGN in the X-ray band

In this thesis we study the AGN environment using X-ray spectroscopy. The current instrumentation for X-ray astronomy allows to perform both a low-resolution, but broadband (i.e., in the 0.3–10 keV band) spectroscopy, and a high-resolution spectroscopy. The former is better suited to study the X-ray continuum emission, while the latter is more useful to study the outflows.

The X-ray continuum

The accretion disk in AGN does not emit much radiation in the X-ray band. The X-ray radiation is thought to be produced in a compact corona of hot plasma located at a distance of some light-hours from the black-hole. The optical/UV photons emitted by the accretion disk gain energy from the encounter with the hot electrons of the corona. Thus, they emerge from the corona as X-ray photons. This is a well-known radiative

phenomenon named inverse Compton effect.
The X-ray spectrum produced by this Comptonization can be approximated by a power-law shape. This is indeed the spectral shape ubiquitously observed in AGN spectra above ∼2.0 keV. On the other hand, at energies below ∼2.0 keV, the spectrum of type 1 AGN often lies well above this theoretical power-law. The origin of this so-called soft-excess is still an open issue.
AGN are variable X-ray emitters. Spectra of the same AGN taken at different epochs may look quite different, both in luminosity and in spectral shape. For instance, the luminosity in the soft X-ray band may decrease of a large factor (e.g., 2–20) and at the same time, the spectrum may undergo significant changes even on a timescale of few hours. In many cases, a time-variable absorption of the X-ray radiation explains well the observed variability. In practice, AGN appear more or less X-ray luminous depending on how much the X-ray radiation is absorbed along the line of sight. This variable X-ray absorption may be due to some patchy cold (i.e. neutral) material located around the inner edge of the obscuring torus, or in some cases, even within the BLR.

Warm absorbers

Roughly half of Seyfert 1 galaxies host a warm absorber (WA) i.e. a gentle ($v_{\rm out}$=few hundreds–few thousands km s^{-1}) outflow of ionized gas. The ionized atoms contained in the winds absorb the nuclear light at a specific frequency. Thus, the spectral signatures of WA are a plethora of narrow absorption lines (NAL) from many ionized species of common atomic elements such as iron, oxygen, nitrogen and carbon. The lines are detected in the UV and X-ray high-resolution spectra of AGN. Because of the motion of the gas towards us, these lines are detected at a frequency which is higher than the laboratory one. This is called Doppler effect. Thus, the shift in frequency of the lines provides a measurement of the outflow velocity of the wind.
The WA material remains steadily ionized because it is constantly illuminated by the AGN light. This is called photoionization. In a photoionized gas in equilibrium, the number of photoionizations (i.e. a photon hits a nucleus a nucleus and an electron is stripped) must be instantaneously equal to the number of recombinations (i.e. an electron rebinds to a nucleus and a photon is emitted). By explicitly computing this photoionization balance, it is possible to predict the concentration of all the ionic species contained in the gas and thus the expected strength of all the absorption lines. This photoionization modeling provides a measurement of the level of ionization of the gas, which is quantified by the ionization parameter ξ, and of its global absorbing power, which is quantified by the hydrogen column density $N_{\rm H}$.
In the last fifteen years, WA have been extensively studied by performing many UV/X-ray observational campaigns of nearby Seyfert 1. A detailed physical picture has emerged. WA are multicomponent winds spanning a range in ionization and in velocity even in the same object. The lines belonging to the most highly-ionized WA components (e.g., Ne IX–Ne X, O VII–O VIII, and, C VI) are detected only in the X-ray, while the least ionized lines are detected only in the UV (e.g., Si II–Si III, Mg II, and, C II–C IV). In some cases, an intermediate phase producing absorption lines in both the UV and the X-ray band (e.g.

O VI), may be present.
Determining accurately the distance r of the WA from the center is often not possible. In principle, provided the gas density n, the ionization parameter ξ, which scales like $1/nr^2$, is a direct indicator of the WA distance. In practice, in most cases no direct density indicator is available and only an order of magnitude estimation of the distance is possible. In fewer cases, the detection in the UV of absorption lines from density-sensitive metastable levels provides a density diagnostic. Measuring the recombination timescale $t_{\rm rec} \sim n^{-1}$ of a particular ione (i.e., measuring the time delay after which an absorption line reacts to changes in the illuminating continuum) is another possible method of determining the density. In order to observe this time delay, it is necessary to perform a time-resolved spectroscopy on a few ks–few days timescale, depending on the source.
Using these methods, the distance of the WA has been determined in a handful of nearby AGN. According to the estimations available so far, WA are often located as far as the obscuring torus. Determining the distance serves also to estimate the amount of energy that the WA delivers in the surrounding environment. This is quantified by the kinetic luminosity $L_{\rm kin} \sim v^3 N_{\rm H}\, r$. It is useful to compare this luminosity with the total AGN luminosity $L_{\rm bol}$ in order to ascertain whether the WA is important for the AGN feedback scenario. For a typical WA, $L_{\rm kin}$ is much smaller than $L_{\rm bol}$. Thus, these ionized winds alone do not contribute much to a possible AGN feedback.

This thesis

In this thesis, we have used X-ray spectroscopy to study circumnuclear gaseous environment as well as the primary emission mechanism in three nearby AGN: 1H 0419-577, NGC 5548, and, 4C +74.26.
The main results are:

- We found that the X-ray WA in 1H 0419-577, detected also in the UV, is part of a galactic wind. Using photoionization modeling techniques, we showed that the optical/UV/X-ray NLR is a complex gaseous environment stratified both in ionization and in density.

- Using optical, UV and X-ray data, we showed that the soft-excess in 1H 0419-577 may be produced by Comptonization of the disk photons in a warm corona, possibly located above the accretion disk. Moreover, we found that the broadband variability of this AGN during ~ 10 years may be due to a variable cold absorber, possibly located around the inner edge of the obscuring torus.

- In 2013, during an extended monitoring campaign dedicated to the the WA in NGC 5548, we discovered the AGN in an unusual condition of heavy and persistent soft X-ray obscuration. We showed that the X-ray variability observed during the campaign is consistent with the picture of patchy wind obscuring our line of sight. This inner wind also filters the light received by the WA, which become less ionized that what was observed during historical unobscured epochs. We confirmed this scenario by analyzing the X-ray lines of the WA.

- Using an high resolution X-ray spectrum, we characterized a photoionized gas outflow in the radio-loud quasar 4C +74.26. This is consistent to be X-ray counterpart of a polar scattering outflow detected in the optical band for this source.