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ACTIVE GALACTIC NUCLEI

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Content

Summary

We recall the discovery of quasars and the long time it took (about 15 years) to build a theoretical framework for these objects, as well as for their local less luminous counterparts, Active Galactic Nuclei (AGN). They all harbor a supermassive black hole accreting gas from its environment. The infalling gas forms an "accretion disk" around a black hole and radiates a fraction of its rest-mass energy. It gives rise to a broad-band spectrum due to thermal processes, extending from the far-infrared to the hard X-ray range. There are indications that the X-ray emission is produced very close to the black hole (at a few gravitational radii), and that the disk extends also quite close. Some AGN and quasars are characterized by an intense radio emission, and are therefore called "radio-loud". The radio emission is due to the synchrotron process from a relativistic jet. It is always accompanied by an intense non-thermal gamma-ray emission. AGN take different aspects according to the angle between the line of sight and the jet (or the rotation) axis. When the jet is directed towards us, the non-thermal emission is relativistically amplified and the object appears as a "blazar", strongly variable and emitting very high energy gamma-rays. More generally the "Unified Scheme" invokes the direction of the line of sight to account for the differences between several classes of AGN: close to the plane of the accretion disk, a thick "dusty torus" blocks the radiation from central regions, like the UV continuum and the broad spectral lines. As an example, powerful radio-galaxies are radio-loud quasars seen at such orientation.

Supermassive black holes span a range of masses from 10^5 to 10^{10} solar masses and are probably present into all galactic nuclei, but with different levels of activity. Only one percent are luminous AGN, and in about 40% galaxies, the central black hole accretes gas at a very low rate. The accretion flow have then a quite different structure from that of luminous AGN, and it seems to be always accompanied by a jet. The mass of the central black hole correlates with the mass of the spheroidal part of the galaxy, most developed in early type (elliptical) galaxies. The formation and the evolution of supermassive black holes are thus tightly linked with the evolution of the galaxies themselves.

1 Historical aspects

1.1 Prehistory

When Marteen Schmidt working at the five meters telescope on Mount Palomar took the spectrum of a faint blue "star", whose position coincided exactly with that of a recently discovered radio-source having the number 273 in the third Cambridge catalogue (thus 3C 273), he certainly did not think he would do a major discovery in extragalactic research. He observed in this spectrum several bright and broad spectral lines located at unfamiliar wavelengths. However, he noticed a regularity in the positions of the four lines: they seemed to be separated in the same way as Balmer series of hydrogen lines, although all of them were strangely shifted by 16% towards the red. What if they are indeed Balmer lines? he wondered. The required redshift corresponded to a velocity of 16% of the speed of light, if it was caused by the Doppler effect. If so, the star was not a star in our Galaxy but a very distant object participating in the expansion of the Universe! He consulted his colleagues and an additional test of the hypothesis was performed. An observation was made in the infrared to check whether one more hydrogen line was there, and it was there, shifted by the same amount! This was reminding of another faint blue star located at the position of the radio source 3C 48, whose spectrum revealed in 1960 intense broad and bright lines also at completely unknown wavelengths (this result was not published at this time). They were thus immediately also identified with the Balmer series and other lines observed in planetary nebulae, this time "redshifted" by 37%.

Except for another radio-source corresponding to a very distant cluster of galaxies, 3C 295, such high redshifts were never observed before. But the two blue "radio stars" were not resembling in any way a galaxy cluster. Nevertheless, it was rapidly admitted by many specialists that their redshifts were indeed "cosmological", i.e. due to the Hubble expansion law, and therefore that "quasars", first baptized "quasi stellar radio sources" [1], were distant by more than a billion light-years and had a luminosity in the visible range (i.e. a radiated power) on the order of 10^{39} Watts. So they were brighter than a thousand galaxies altogether. But it was also discovered that 3C273 was variable in a time scale of a week. According to the causality principle, it means that its size should be smaller than a light-week, i.e. a millionth of a galaxy diameter, otherwise the different parts of the source could not communicate in order to establish a common variability pattern, and variations would be smeared by the time it takes the light to cross the object. Finally,

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[1] The fact that they are "stellar-like" means that their size is smaller than the resolution given by the atmospheric turbulence, close to one arc second.

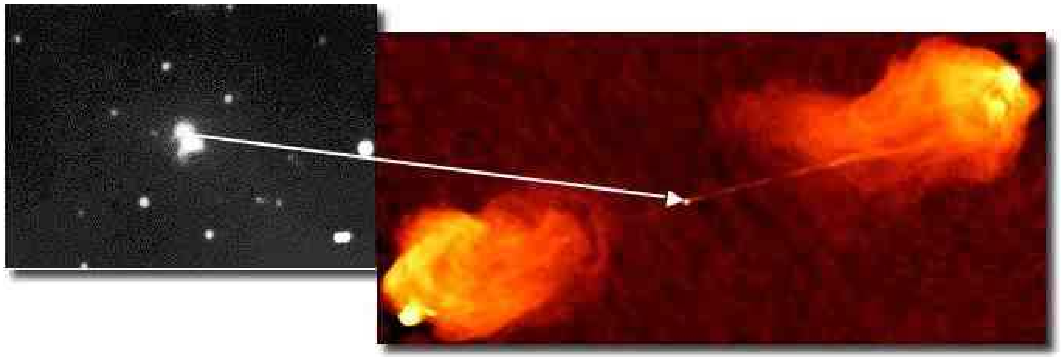

Figure 1: The radiogalaxy Cygnus A. On the left, a visible image as it was observed by Baade and Minkowski in 1954. On the right, a recent radio map of the galaxy, showing two big lobes linked to the galaxy (which is in the center) by a thin jet. Notice the "hot spots" at the extremities of the radio lobes. Source: NRAO.

they were relatively common objects, as hundreds of similar ones were discovered in a few years and tens of thousands are known now, some of them being distant by more than 13 billions light-years [2], their light reaching us after a travel lasting almost as long as the age of the Universe.

All this raised very difficult problems, and some people argued that the cosmological interpretation of the redshift was wrong, and that it was necessary to invoke a still unknown physical law to explain the redshifts. This started the "redshift controversy" which lasted during about 15 years and occupied a large fraction of the meetings during all this time. The discoveries concerning quasars were indeed so unprecedented and not immediately understandable, that they permanently provoked hard debates and created the idea that something else than the known physical laws was at work. The cosmological origin of their redshift is now well established, because quasars are observed in clusters of galaxies whose redshifts are well-known, and because galaxies with known and relatively high redshifts are located on the line of sight between us and quasars and produce imprints in their spectrum. Finally, high quality observations made by the Hubble Space Telescope allowed to see host galaxies harbouring the nearest quasars.

The discovery of quasars could have been anticipated and actually *was* anticipated in the fifties by Geoffrey Burbidge, but very few people realized at this time the importance of his assessments. A new science was developed when radars built during World War 2 were pointed towards the sky: radio-astronomy. It revealed intense sources of radio light whose origin was soon attributed to synchrotron radiation. These electromagnetic waves are emitted when highly relativistic charged particles - mainly electrons - are moving in a magnetic field. In 1954 two of the most intense radio-sources were identified by Baade and Minkowski with M87 (the largest galaxy of the Virgo cluster, called also Virgo A) and with Cygnus A (Figure 1), a faint distant galaxy seeming to be made of two galaxies in collision (this is a very important aspect of the story, as we shall see later). So these sources appeared about 1000 times more luminous in the radio range compared to other galaxies like the Milky Way for instance.

Since the intensity of synchrotron radiation depends on the energy density of the particles and on that of the magnetic field, Burbidge made the assumption that these quantities were equal and he obtained the total energy of the system (it corresponds actually to a minimization of the total energy). The result was that 10^{54-55} Joules was stocked in extragalactic radio-sources, corresponding to the complete transformation of $10^{7-8}\mathrm{M}_{\odot}$ into pure energy. Burbidge thus raised immediately the question of the origin of this enormous energy. His result was largely premonitory since thirty years later it was recognized that radio-galaxies and quasars have the same central engine, and moreover that powerful radio-galaxies are radio quasars seen at a different view angle.

Another birth of the subject can be dated to the study of six peculiar galaxies by Carl Seyfert in 1943 (Figure 2). These galaxies are characterized by bright stellar-like nuclei, with blue color and broad bright lines in its spectra. Seyfert attributed the widths of the lines to Doppler effect caused by the motions with randomly oriented velocities as high as 8500 km s^{-1}. Later, these six galaxies, as well as many other similar galaxies, were called "Seyfert galaxies".

The article by Seyfert was referred for the first time only 16 years later, in two papers published in the same issue of the Astrophysical Journal in 1959, the first one by Margaret and Geoffrey Burbidge, with

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[2] Actually their light have traveled during 13 millions years, but their real distance is much larger than 13 millions light years, according to the expansion of Universe.

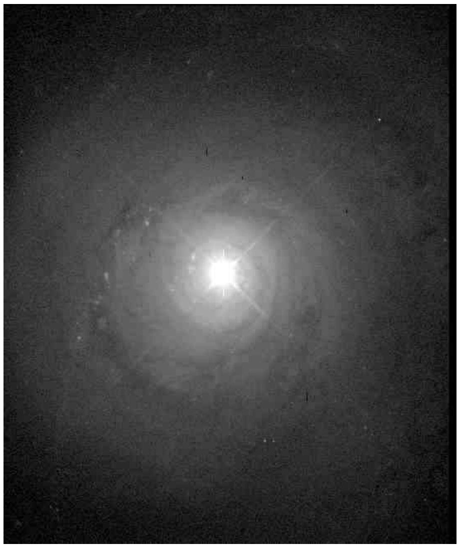

Figure 2: An image of one of the six galaxies studied by Seyfert, NGC 5548, obtained with the Hubble telescope. It shows the bright and starlike nucleus. Source: HST.

Kevin Prendergast, and the second by Lodewijk Woltjer. The Burbidges and Prendergast concluded from a study of the rotation curve based on the stellar velocities that the gas in the nucleus of the Seyfert galaxy NGC 1068 had too large velocity to be kept in by the strength of the gravity, and it should be ejected from the nucleus. On the contrary, Woltjer concluded from a discussion of the properties of *all* six Seyfert galaxies that the gas should be gravitationally confined by a very massive body of a billion solar masses. Both were right: at present we know that there is a large compact mass — a black hole — in the nucleus of every Seyfert galaxy, but we also know that the gas emitting some of the spectral lines is indeed outflowing. This discussion was probably the departure point and a part of the more general redshift controversy.

1.2 After the discovery of quasars

Immediately after the discovery of quasars, their similarities with some local objects appeared evident. The most obvious analogues were Seyfert nuclei. In a sense it was a premonitory idea since, at this time, Seyfert nuclei did share with quasars only their small size, their blue color, and their broad and intense emission lines. Quasars are about two orders of magnitude more luminous than Seyfert nuclei, and one did not know that their broad band spectra and their variability properties, in short all their properties, were exactly the same as those of Seyfert nuclei. The fact that quasars were nuclei of galaxies in a luminous phase was demonstrated definitively only twenty years later, when the pictures obtained with good receptors on large ground-based telescopes and on the Hubble telescope allowed to distinguish the "host galaxy" surrounding the quasar.

Radio-galaxies were also soon considered as being related to quasars, owing to the large amount of energy released in the extended radio structure. Powerful radio galaxies are surrounded by two more or less symmetric radio "lobes" extended up to millions of light years on both sides of the galaxy, and the galaxy itself contains a compact radio source. A very thin elongated radio "jet" extending between the galaxy and the lobes is also observed, often only on one side of the galaxy (see Figure 1). After the development of Very Large Baseline Interferometry (VLBI) in the seventies, the structure of the compact source was resolved, and for the first time in 1978 one got the proof that a tiny source with a dimension of one light year located *inside the galactic nucleus* was the origin of the jet and the radio lobes (and of all the energy stocked in them), as beautifully seen in the case of NGC 6251 (Figure 3). So radio galaxies, Seyfert nuclei, and quasars, appeared clearly linked with some kind of "activity" taking place inside the nucleus of a galaxy. A bunch of other types of objects were also considered as related to quasars. The reasons of this great diversity became clear only after the discovery of the "Unified Scheme" discussed below.

During almost 20 years, no consensus was reached on the origin of the enormous power of quasars associated with a very small dimension. Several models were proposed: front collisions of stars with a high velocity, explosions of supernovae in chains, "flares" at the galactic scale, etc. The most popular was the

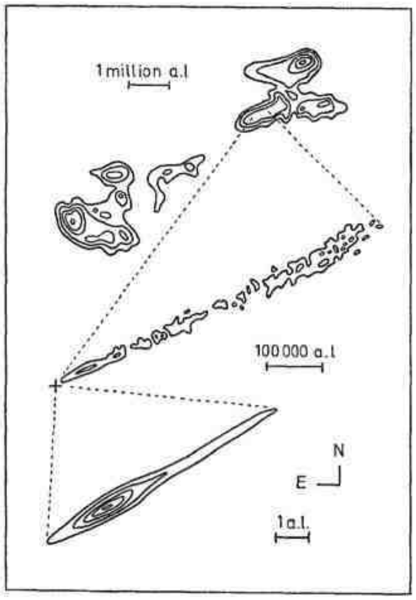

Figure 3: A radio map of the galaxy NGC 6251 at different scales, as it was published in 1978 by Readhead, Cohen and Blandford. It shows clearly that the large radio lobes are ejected by a tiny source at the position of the galactic nucleus. Courtesy Roger Blandford.

“supermassive star” energized by nuclear reactions or by pulsations leading to gravitational release. After the discovery of the first pulsars in 1968, “supermassive rotators” were also privileged, because massive stars are highly unstable and can be stabilized by rotation. All these models had theoretical problems and they did not agree with the observations when the properties of the electromagnetic spectrum were better known, so they had to be finally abandoned.

However, some people have guessed immediately the correct explanation. Already in 1964, two well known astrophysicists, the American Salpeter and the Russian Zel’dovich, suggested independently that a massive black hole was present in these objects, and Salpeter proposed that the matter and the angular momentum transport required for accretion onto the black hole was accomplished via a turbulent viscosity (this is exactly the presently accepted view). But astronomers at first did not take this idea seriously. Though black holes became rapidly quite popular among theoretical physicists, most astronomers considered them as an utopia, in no case associated with energy release in quasars. Lynden-Bell reiterated the proposition in 1970 at the Vatican Conference on “Nuclei of Galaxies’, but the 25 famous astronomers attending the meeting did apparently not realize that this model could be the right one.

After the discovery of “stellar black holes” in binary systems, the idea that black holes could exist begun to be accepted, all the more so that neutron stars - also strange bodies whose existence was predicted already in the thirties - have been discovered as pulsars a few years before. Then Martin Rees produced in 1977 what he called “the flow chart” of a galactic nucleus: he showed that its fate is to lead inevitably through several different ways to the buildup of a “Super-Massive Black Hole”, million to billion times more massive than a stellar black hole, in less than the lifetime of the galaxy itself. More and more people gave thus their adhesion to the model, since supermassive black holes were considered this time in a realistic astrophysical context.

Part of the difficulty with the acceptance of the accretion onto massive black holes as the source of activity came from the fact that the first discovered objects - radio-loud quasars - showed directly the effect of ejection from the nucleus, in the form of spectacular jets. This outflow, as well as the presence of relativistic particles emitting synchrotron radiation, seemed to imply some explosion mechanism. The solution to the puzzle came with time. First, Sandage found soon some “radio-quiet” quasars; they are actually ten times more numerous than radio-loud quasars. Then, in 1978, Greg Shields found the key argument: he showed that the optical and ultraviolet light of some quasars was better explained not by the synchrotron mechanism, but with another mechanism, this time directly related to the black hole: the radiation of an “accretion disk” driving the gas towards the black hole. One can consider that it was the death knell to the other models, and the real beginning of the "accretion onto a supermassive black hole" paradigm for the central engine of all objects with active nuclei. We now know that active galaxies, when eating, spill out some fraction of the soup but it is the eating that keeps them alive.

Since the basic mechanism operating in quasars, radiogalaxies, Seyfert galaxies, and all other galaxies with nuclei showing non-stellar emission, is the same, we now frequently refer to all these objects as "Active Galactic Nuclei", or shortly AGN.

1.3 Accretion onto Supermassive Black Holes: why it works so well?

Like all massive objects, black holes attract surrounding material. Gas "falls" onto the black hole while emitting radiation, exactly like a shooting star which is heated and partly evaporated in the earth atmosphere. In the case of a black hole, the amount of radiated energy can be very large, up to 30% of the rest mass energy of the falling body, $\mathrm{m_0c^2}$. This is possible because an infalling particle reaches a velocity close to the speed of light, thus gaining a very large kinetic energy at the expense of the potential (gravitational) energy. A significant fraction of this energy can be ultimately converted into heat and radiated away before the particle crosses the black hole horizon. The fraction of the rest mass converted into energy is thus much larger than the 0.7% obtained in stars energized by nuclear reactions. This is already a good reason to prefer accretion onto a black hole to any other process of energy production, because it minimizes the fuel rate, and thus the mass, of the "central engine".

The masses involved are nevertheless huge, as we can easily estimate. The black hole (or any other object) cannot be powered by accretion and radiate this energy away at an arbitrarily rate. If the emitted radiation is too high, the radiation pressure more than counter-balance the force of gravity and the surrounding material starts to be expelled. Thus, the luminosity of an object cannot rise above the value called the "Eddington luminosity" L_{Edd}, equal to $1.5\ 10^{40}\frac{M(\mathrm{BH})}{10^9\mathrm{M}_\odot}$ Watts, where $\mathrm{M}_\odot$ is the mass of the Sun. 10^{40} Watts is about the power of 3C 273 (if one takes into account the fraction of energy radiated in the non-visible range). Assuming that quasars are radiating close to their Eddington luminosity (it is actually the case) implies that the mass of the central object is about $10^9\mathrm{M}_\odot$.

Another circumstance pleas also strongly in favor of the black hole hypothesis: it minimizes the size of the engine, and the estimated sizes are consistent with observational constraints.

The theory of black holes is a major subject of theoretical studies, and we mention here only a few simple properties. Light or matter cannot escape from the black hole interior surrounded by a sphere where the escape velocity is equal to the light speed. This sphere is called the "horizon" of the black hole. For a non-rotating black hole, its radius is called the Schwarzschild radius, R_{Schw}, and it is equal to $3\ 10^{12}\frac{M(\mathrm{BH})}{10^9\mathrm{M}_\odot}$ meters (note that the radius is proportional to the mass, so the bigger the mass, the less the *average* density). We have seen that the variation time scale of 3C273 is about a week, indicating a size of the emission region of $3\ 10^{14}$ m, i.e. about 100 R_{Schw} for a black hole of $10^9\mathrm{M}_\odot$. Such a size is comfortably larger than the black hole horizon, and actually quite consistent with more accurate theoretical considerations about the emission from accretion flow. At present the most tight constraints for the size of the optical emission of a quasar came from the gravitational lensing observed in the quasar Q2237+030 known also as the Einstein cross (2×10^{13} m).

The gas does not dash radially for the black hole, as its initial velocity is not necessarily (and even is never) directed exactly towards the center. It goes there by spiraling around the black hole, with the radial velocity frequently much smaller than the rotation velocity (the rotation velocity at the Schwarzschild radius is close to the light speed). In other words, the gas falls towards the black hole very slowly via an "accretion disk". A great challenge was to understand how this disk worked, and in particular how the gas was able to loose its angular momentum.

Thus at the beginning of the eighties a theoretical framework was available to elaborate a detailed physical model for the central engine of quasars and AGN. Fortunately, space missions were beginning to provide abundant information on their emission properties in infrared, ultraviolet, X and gamma bands.

2 The emission properties of radio-quiet quasars and AGN

In this section we concentrate on the description of the relatively bright AGN, with unobscured view towards the nucleus and without very strong radio emission. These objects give us the best possibility to observe

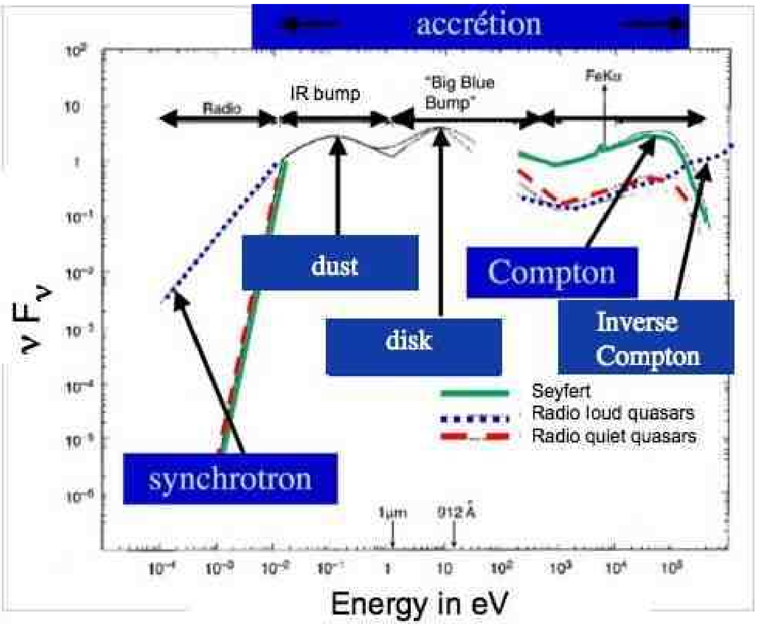

Figure 4: The typical Spectral Energy Distribution (SED) of quasars (radio-loud and radio-quiet) and radio-quiet active (Seyfert) galaxies, after Sanders et al. 1989. Seyfert and radio-quiet quasars have no radio and gamma-ray emission.

the accretion pattern onto a central black hole. Good examples of such objects are radio-quiet quasars and some of the Seyfert galaxies.

2.1 The broad band spectrum: the "accretion emission"

AGN are characterized by a "continuous" emission extending all over the electromagnetic spectrum, from the far infrared up to the hard X-ray range (Figure 4). Such broad-band data, as shown on the plot, were mostly collected with the use of satellites. Nevertheless, the spectral coverage is not complete since the extreme ultraviolet emission is obscured both by the Earth atmosphere and by the neutral hydrogen in our Galaxy. It introduces considerable uncertainty in the analysis of this emission. The spectrum can be actually divided into three components or "bumps". They are emitted by regions whose distance from the center increases with the wavelength, as it is assessed by their variability properties:

- 1. The infrared bump is constant in time scales of years and is thus probably emitted in a region larger than 10 lyrs (between 10^4 and 10^6 $R_{\rm Schw}$).
- 2. The "Big Blue Bump" extends from the optical to the extreme ultraviolet, and even to soft X-rays. This component contains the dominant part of the total luminosity. It varies within time scales of days/years; it is produced by a region $\sim 10 - 100 R_{\rm Schw}$.
- 3. The X-ray bump varies within time scales of hours/days and is thus emitted by a small region, most probably close to the black hole ($\sim 10 R_{\rm Schw}$).

The presence of distinct spectral components indicate the presence of three separate physical components in the accretion flow.

The infrared bump is likely due to dust heated by the central ultraviolet and X-ray source, either in the outer regions of the accretion disk itself, or farther away in the "obscuring torus" accounting for the "Unified scheme" of AGN (cf. later).

The Big Blue Bump and the X-ray bump are most probably emitted by the inner regions of the accretion disk. Let us shortly describe how an accretion disk works. When the gas particles go closer to the black hole, the rotation velocity increases, so the kinetic energy increases at the expense of the potential energy, because their sum (the total energy) must be preserved. The kinetic energy can then be converted into thermal energy and radiated away, allowing the gas to come even closer to the center. Performing such

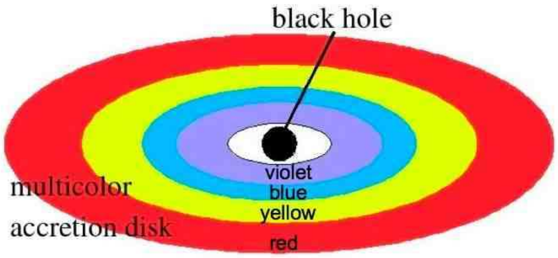

Figure 5: Schematic picture of the multicolor accretion disk around a black hole. The disk temperature is higher close to the black hole and lower at larger radii.

steps, the gas gives rise to the observed emission. Surprisingly, the simplest case for understanding is that of an inflow of material with high angular momentum. The gas particles then circulate around the black hole almost at circular orbits, only slowly drifting from one orbit to another. Since the total energy at circular orbit of radius R is equal to half of the potential energy (-1/2 GM/R), the second half of the energy has to be radiated away. Crossing from one orbit of somewhat larger radius to another of somewhat smaller radius the particle has to radiate the difference between the total energies characteristic for these orbits, and this emission is radiated away from both sides of the narrow ring between the two orbits. The total emission from the ring is proportional to the number of particles passing from one orbit to another, i.e. the accretion rate, $\dot{M}$. Thus the total flux is a simple function of the disk radius, the black hole mass and the accretion rate, $F \propto \mathrm{G}M\dot{M}/R^3$, independently on the details of the flow, including the viscosity mechanism. If the disk is optically thick and emits like a black body, so $F = \sigma T^4$, where σ is called the Stefan constant, we even know the temperature distribution across the disk.

If different regions of the disk could be observed directly, the disk would appear like a multi-colored dish, whose color is red outwards and becomes progressively bluer, then violet and ultraviolet towards the interior (Figure 5). The optical emission corresponding to a temperature of about 10^4K comes from $\sim 10^3 R_{\mathrm{Schw}}$ while extreme ultraviolet radiation corresponding to a temperature of a few 10^5K is emitted typically at $\sim 10 R_{\mathrm{Schw}}$. Closer to the black hole, more complex formulae from general relativity must be used. The important effect is the existence of the innermost stable circular orbit (at 3 R_{Schw} for non-rotating black hole and closer in for a rotating one). The accretion disks ends there in a sense that the material from this orbit effortlessly plunges into the black hole as the gravity finally wins even over the angular momentum barrier. Unfortunately, the disk is much to small to be spatially resolved with the current instrumentation.

A difficulty is raised with this model by the observation of the "X-ray bump" extending up to hundreds of keV (see Figure 4). Hard X-ray emission is not predicted by the simple theory of accretion disks (contrary to X-ray stars which radiate in hard the X-ray range, because the masses of their black holes are about 10^{6-8} times smaller than those in active nuclei). The X-ray spectrum can be decomposed in several components: a hard power-law (i.e. the logarithm of the intensity is proportional to the logarithm of the frequency) with a turnover at a few tens keV, a soft X-ray excess, and a "reflection" component made of backscattered X-rays due to the irradiation of a surrounding "cold" medium, most probably the accretion disk itself (Figure 6).

The presence of the reflection component is confirmed by the observation of an iron line at 6.4 keV, due to fluorescence (it is not seen in X-ray luminous objects, probably because iron is then too much ionized). This line displays often a peculiar profile with a broad red wing (Figure 7). Such a profile proves that the line photons have undergone a strong gravitational redshift, meaning that the line is formed sometimes at only one or two Schwarzschild radii from the black hole. The fact that the line is formed so close to the black hole is extremely important for testing the black hole rotation. If the black hole is not rotating, the gas should indeed plunge radially without radiating when it reaches $3R_{\mathrm{Schw}}$. But if on the contrary it is rapidly rotating (it is then called a Kerr black hole), the surrounding space itself is dragged into the rotation, and the gas can thus be spiraling and emitting down to $0.5R_{\mathrm{Schw}}$. So the extension of the red wing provides a diagnostic of the accretion flow in the strong gravity field of the black hole, and the issue is currently vigorously studied with new X-ray instruments.

In the most widely accepted model, the disk is thus made of two parts:
- the standard "cold" disk transporting the matter inward and radiating as the Big Blue Bump,
- a hot optically thin corona surrounding the inner regions of the disk emitting X-rays.

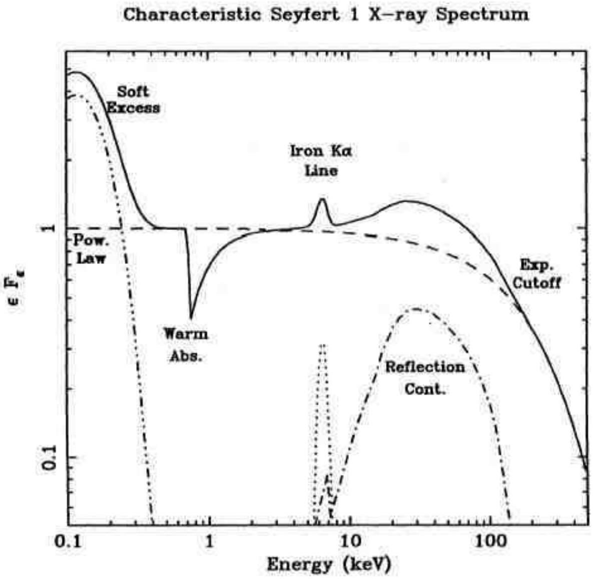

Figure 6: The different components of the X-ray spectrum. Source: A. Fabian, in Theory of Black Hole Accretion Disks, CUP 1998.

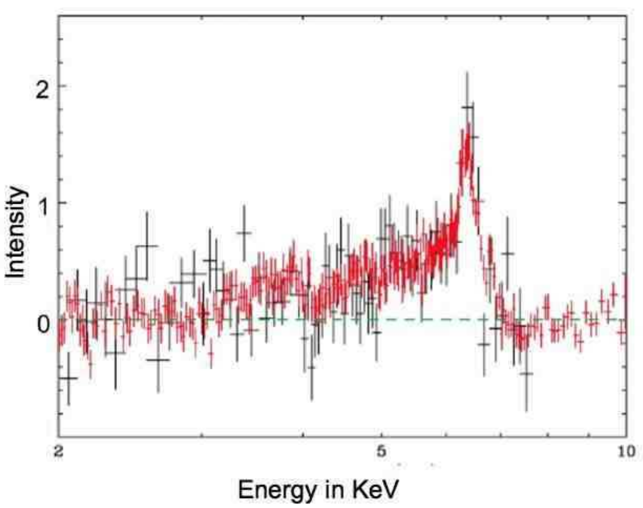

Figure 7: Profile of the FeK line in MCG -6-30-15, observed by the X-ray missions Chandra and XMM-Newton, showing a very extended red wing. Source: A.J. Young 2005.

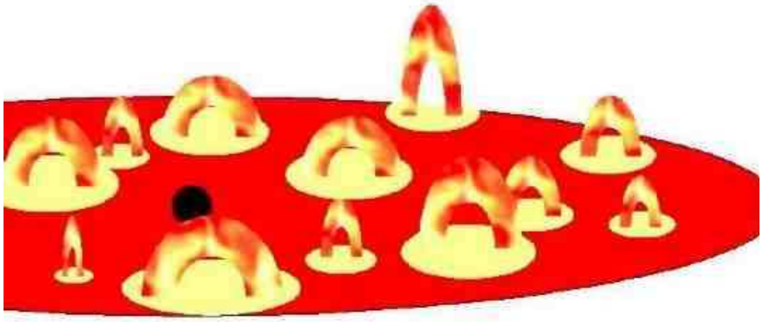

Figure 8: Schematic picture of the magnetic flares emerging from the accretion disks. The disk ultraviolet radiation is Comptonized by the hot flare plasma, and the energetic X-ray photons created in such way illuminate in turn the disk surface in the flare vicinity.

The corona is likely to be made of a few active regions similar to solar flares, sustained by magnetic loops anchored in the accretion disk (Figure 8). The X-ray emission of the plasma is caused by the Comptonization of the softer, less energetic optical/ultraviolet (e.g. disk) photons. A sketch of such scenario is shown below. However, the exact geometry of the hot plasma is still under discussion, and the key question is whether the cold disk continues all the way down to the last circular orbit, or is actually disrupted at 10 R_{Schw} or more, and replaced by the optically thin hot flow. The shape of the iron line mentioned before in principle contains the answer to this question since the line forms only in the cold/disk part of the flow, but the interpretation of the observational data at present is not quite unique. What is more, the flow properties are likely to depend on the Eddington ratio, i.e. the ratio of the object luminosity to its Eddington luminosity. We will return to this issue in Sect. 3.5.

Until now, we have not mentioned the fate of stars orbiting in the vicinity of the black hole: like the gas, they are attracted by its enormous mass. When a star approaches very close to the black hole, it is disrupted by a huge tidal effect, because the gravitational potential is larger on the side of the star facing the black hole than on the other side. The denser the star, the closer it can approach the black hole without being disrupted: compact stars like white dwarfs, neutron stars or stellar black holes are always swallowed by a massive black hole without being broken. Moreover, if the radius of the black hole is large enough (remember that the radius is proportional to the mass) tidal effects do not occur before the stars have penetrated inside the horizon. As a consequence, all stars except supergiants are swallowed without being disrupted by a black hole more massive than 3 10^8 $M_\odot$. If the black hole is less massive than 3 10^8 $M_\odot$, "main sequence" stars like the sun are broken up and transformed into hot gas which is accreted via the disk after having radiated a fraction of its thermal energy, thus contributing to the luminosity. Such a phenomenon has probably been observed as it is the most likely explanation of sudden temporary increase of the X-ray flux lasting for about a year, seen in several, generally non-active galaxies.

2.2 Optical, ultraviolet, and X-ray emission lines

We recall that the spectra of quasars and Seyfert galaxies present intense broad lines in emission in the optical and ultraviolet band. Lines in the ultraviolet can easily be observed in quasars because they are redshifted and sent to the optical range. For Seyfert galaxies, it is only after the launch of the space missions like Ultraviolet International Explorer (IUE) in 1978 and thereafter the Hubble telescope, that they were observed. These lines are considered as a signature of the presence of a supermassive black hole.

Spectral lines are due to transitions between two energy levels of an atom. Such energy levels are specific for an atom. Lines are seen in emission when the transition occurs from an upper to a lower energy level. To simplify the explanation of the process, one can say that an electron belonging to the atom falls from an upper to a lower level, loosing a quantified amount of potential energy. This energy is given to a "line photon" which escapes from the medium. A transition can also occur from a lower to an upper level, when a photon is absorbed: it leads then to "absorption lines", like those observed in stellar spectra; in this case, the underlying continuum radiation coming from the interior is absorbed when it passes through the atmosphere. The fact that lines in active galaxies are in emission implies that the size of the region emitting the continuum is much smaller than the size of the region producing the lines, as illustrated in Figure 9.

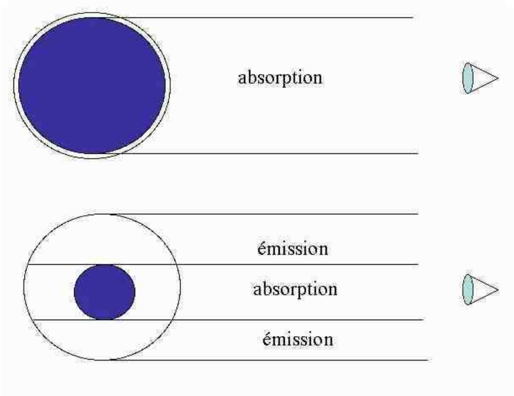

Figure 9: Schematic picture of the formation of emission and absorption lines. When the source of continuum is as large as the source of lines, one sees absorption lines, and inversely.

There are two kinds of lines. Some of the lines (like the [OIII] lines at 4959-5007 Angströms, which are due to twice ionized oxygen atoms) are "forbidden". This strange expression means that they are not observed on Earth because they require a peculiar condition - an extremely small density - which cannot be achieved even in a laboratory. When they were discovered in planetary nebulae at the beginning of the twentieth century, they were attributed to an unknown element called "nebulium" (but it was not expected by Mendeleev table!), and their nature was understood only thirty years later[3]. In the case of forbidden lines, the "excitation" of the upper level is caused by a collision of the atom with another particle, generally an electron, which loses a fraction of its kinetic energy and gives it as potential energy to the atom. Generally, the inverse mechanism also occurs and leads to the "de-excitation" of the upper level without the emission of a photon. The distinctive feature of forbidden lines is that the upper level has a very long lifetime, so a line photon is emitted only after a long time. If the medium is dilute, collisions are infrequent, a collisional deexcitation is not very probable before the photon is emitted. The presence of these lines implies thus that the medium is very dilute (and therefore extended, also consistent with the fact that the lines are seen in emission).

The second type of spectral lines (like the Balmer or the Lyman series of hydrogen) are "permitted", because their upper level has a short lifetime, and line photons are very easily emitted. These levels can be also excited by collisions, but generally another mechanism produces the line emission. When a high energy photon is absorbed by an atom, it can remove an electron from the atom (which is then "ionized"). After that, the ionized atom can capture another electron on a high energy level. The electron falls onto lower levels by successive "cascades", and at each cascade step a low energy photon is emitted. In short, a high energy ultraviolet photon is transformed into several optical photons. It reminds us of the "fluorescence" process well-known on Earth.

As already mentioned, the line widths in AGN are attributed to Doppler motions. It was early recognized that the permitted and the forbidden lines are not broadened similarly. The widths of the forbidden lines correspond to velocities of a few hundreds of km s^{-1}, while those of the permitted lines correspond to velocities of a few thousands of km s^{-1}. It means that they come from two different media. Moreover, the region emitting the "narrow lines" is spatially resolved in nearby Seyfert nuclei, with a typical dimension of a few hundreds of parsecs, while the region emitting the "broad lines" is not resolved. These two regions must have different densities: in the region emitting the forbidden lines, the density must be smaller than 10^6 particles per cubic centimeter (a value smaller by 15 orders of magnitude than that of the Earth atmosphere!). And since no forbidden lines are observed in the region emitting the permitted lines, one deduces that they are "collisionally de-excited", implying that the density is larger than 10^6 particles per cubic centimeter (from the study of the line intensities, one deduces that it is in fact at least 10^{10} particles per cubic centimeter). These regions were thus named "Broad Line Region" or BLR, and "Narrow Line Region" or NLR. In the seventies, one begun to make the distinction between two types of Seyfert nuclei: type 1 Seyfert galaxy, with both broad and narrow lines, and type 2 Seyfert galaxy, with only narrow lines. The reason of this difference

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[3] The same story happened for a line observed during solar eclipses and attributed to an unknown element called "coronium"; it is actually also a forbidden line, this time of highly ionized iron.

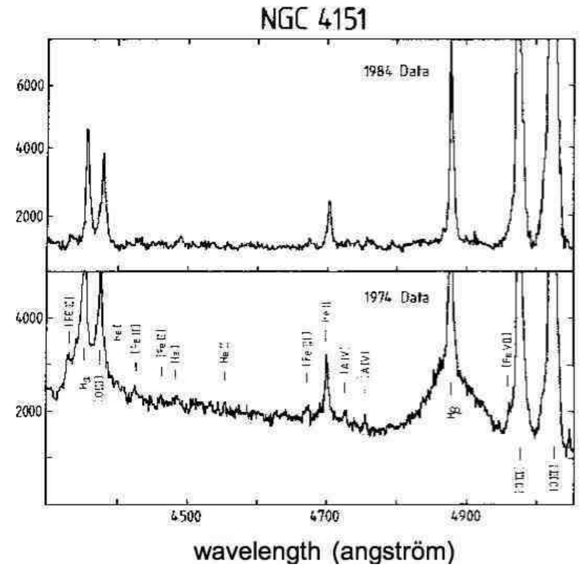

Figure 10: Example of the optical spectrum of the Seyfert galaxy NGC 4151: it changed in 10 years from a type 1 Seyfert (bottom) with broad and intense hydrogen lines to a type 2 Seyfert (top) with only narrow lines. Interpreted in the framework of the Unified Scheme, it means that this nucleus is seen close to the edge of the absorbing "torus", and some material intercepts the line of sight from time to time. Credit M.V. Penston, E.Perez 1984

was not understood at this time. It was also noticed that quasar spectra look much more like Seyfert 1 than Seyfert 2 spectra (cf. Figs. 10 and 11 showing the spectrum of types 1 and 2 Seyfert, and a typical quasar spectrum).

If the gas is gravitationally bound to the black hole, its velocity is of the order of $\sqrt{2GM/R}$. At the distance of the NLR, it should be smaller than 100 km s^{-1}, in contradiction with the observations. It means that the gas in NLR is escaping. Recent high quality observations with the use of the Hubble Space Telescope actually showed an outflow pattern in many objects: radial velocities first increase with the distance from the nucleus, reach a maximum and then decrease. This new result agrees with the old conclusion of the Burbidge and Prendergast in 1959 concerning the type 2 Seyfert nucleus NGC 1068. In contrast, the BLR would be gravitationally linked with the black hole if its dimension is smaller than 1/10 pc. It is actually of this order, for instance in 3C273, since it is observed to vary in time scales of weeks or months. So the BLR is most probably gravitationally bound to the black hole.

The presence of emission lines of multiply ionized atoms proves the existence of an underlying ionizing ultraviolet continuum, also in objects where the Big Blue Bump component is not well seen. The source of continuum - the inner regions of the accretion disk - is much smaller than the BLR (typically 1/100 pc for a black hole of 10^9 M$_\odot$), and this property had a great impact on the studies of AGN. The broad lines being excited by the central source of continuum, should respond to its variations after a time delay on the order of the dimension of the BLR, R(BLR), divided by the speed of light. Thus a project was formulated to determine R(BLR) and the velocity of the gas in a number of Seyfert nuclei and quasars. This technique, in a sense similar to tomography in medicine and called "reverberation mapping" was suggested in 1982 by Blandford and McKee. It consists of measuring the line profiles (intensity as a function of wavelength around the line center) and the time delays between the variations of the line and the continuum flux. Intense monitoring campaigns, lasting for 20 years in some cases, were organized on different telescopes. The results were not anticipated. Though they did not reveal the detailed structure of the BLR as expected, they were able to give an estimate of the masses of the black holes in several dozen of quasars and Seyfert galaxies: we had the radius from reverberation, we had the velocity from the width of the line and this was enough to determine the mass assuming circular or random motion in the gravitational field of the black hole. In the course of these studies, the existence of an empirical relation between the BLR radius and the luminosity of the object was discovered (again unexpected). It allowed to determine the black hole mass *from a single spectroscopic observation of an active galaxy* by measuring just the line width and the luminosity in thousands of quasars and fainter AGN.

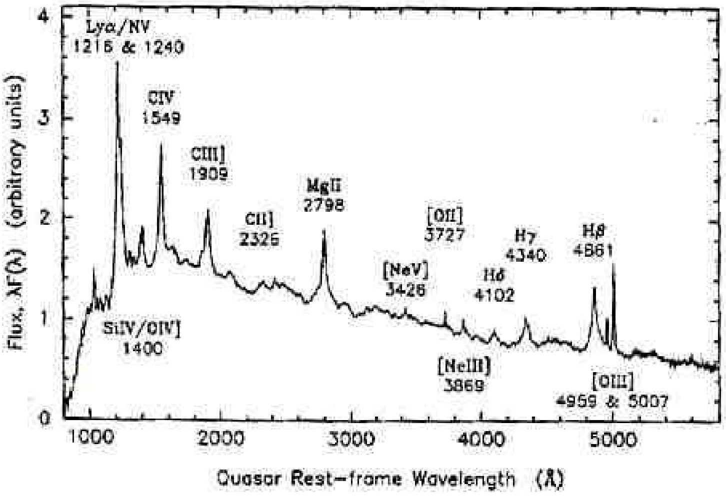

Figure 11: A synthetic quasar spectrum, obtained by adding spectra of quasars having different redshifts. Comparing the region of Hβ-[OIII] lines, one sees that the spectrum is similar to that of a Seyfert 1.

There is another important use of spectral lines. Both forbidden and permitted lines are emitted by highly ionized atoms, like Iron 6, 9 or 13 times ionized, Oxygen 3 or 5 times ionized, Neon 4 times ionized, etc. The relative intensities of the lines of the same ion, and those of different ions, can be estimated using numerical codes which allow to determine the physical conditions - pressure, temperature, dimension - of the emitting medium, given some free parameters. These free parameters are determined when the computed lines agree with the observed ones. This is a well-known technique in astrophysics called “modeling”. This method allows, for example, to deduce the distribution of the intensity in the continuum, and in particular the shape of the Big Blue Bump, which is not completely accessible to direct observations in its extreme ultraviolet/soft X-ray part as it is strongly absorbed by interstellar hydrogen atoms. It is an important clue for the accretion mechanism, as the Big Blue Bump contains the bulk of the radiated power.

2.3 Ultraviolet and X-ray absorption lines: the wind

Absorption lines are also observed in the spectra of AGN, particularly in quasars. It is important to distinguish between two types of absorption (they were confused together for many years): lines which are intrinsic to quasars, and lines due to interstellar or intergalactic clouds on the line of sight to a quasar, but having nothing to do with it.

Almost immediately after the discovery of quasars, narrow absorption lines lying at the blue side of emission lines were observed. They were immediately attributed to an outflow coming from the quasar: since the absorbing gas is located on the line of sight and is less redshifted than the object, it means, according to the Doppler effect, that the gas is moving towards us. This explanation was reinforced by the discovery of absorption features in the blue wing of emission lines, this time very broad and exhibiting a classical profile well-known in “P Cygni stars”, which is the signature of a wind outflowing from a central body. Later, these lines were called “Broad Absorption Lines” or BALs. They are observed in about 10% of quasars (Figure 12).

In the following years, many systems of very narrow absorption lines were discovered, frequently with redshifts very different from those of the emission lines (but always smaller). It is now evident that these systems are due to intervening galaxies on the line of sight of quasars. A rich branch of cosmology developed on this subject, especially when a bunch of absorption lines, all due the transition Lα of hydrogen at different redshifts, started to be detected in the spectra of distant quasars. These lines, called the “Lα forest”, are due to intergalactic clouds which were not massive enough to form galaxies, and are constituted of primordial elements like hydrogen and helium, with an extremely small amount of “heavy” elements processed in stellar interiors (Figure 13).

In contrast, Broad Absorption Lines are indeed due to gas outflowing from quasars, with a velocity reaching in some cases 20000 km s^{-1}. Intrinsic absorption lines are also observed in Seyfert nuclei, but with smaller intensities and velocities than in quasars. They have a counterpart in the soft X-ray range (i.e.

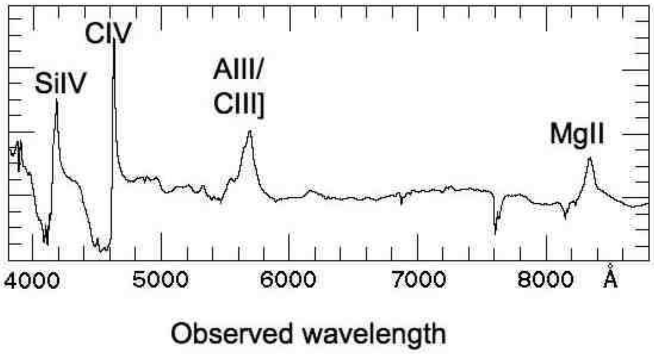

Figure 12: Spectrum of the first discovered "Broad Absorption Line" quasar, PHL 5400. It shows broad absorption lines present in the ultraviolet wing of emission lines. After Cohen et al. 1995.

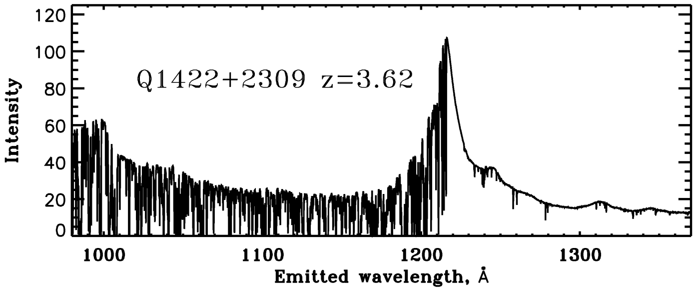

Figure 13: Spectrum of a quasar showing many narrow absorption lines in the ultraviolet wing of Lα, forming the "Lα forest". Courtesy: W.C. Keel.

between 0.2 and 2 keV) in about 50% of type 1 Seyfert nuclei, where there is a rich absorption spectrum detected with recent spatial missions. Neither the physical mechanism giving rise to the wind, nor whether ultraviolet and X-ray absorption lines have the same origin, is now clear. Also one does not know whether all quasars and Seyfert nuclei have such winds, but they can be observed only in a fraction of them (due to viewing angle for instance, as explained below), or whether they are present only in a fraction of objects. They could transport an appreciable amount of gas, perhaps as large as the accreted one. At least, one thing seems clear: Broad Absorption Lines are much more frequently observed in radio-quiet than in radio-loud objects, and this is certainly a fundamental result to take into account when trying to understand the difference between both types of objects.

2.4 Variability

AGN are seen to vary in most energy bands. Some radio-loud objects vary particularly strongly, but as before we will concentrate here on bright radio-quiet AGN since they best indicate the accretion pattern.

The amount of observational data on AGN is huge but nevertheless it is not enough to provide us with the deep understanding we hope for. It may be partially related to the fact that most of the variability seemingly originates in the region responsible for the extreme ultraviolet emission which is obscured by the Galaxy. This insight was provided by the multi-wavelength observational campaigns performed for a few selected objects, mostly bright Seyfert 1 galaxies.

An increased/decreased emissivity of the extreme ultraviolet emitting regions propagates both towards the short and the long wavelengths as seen from the measured delays of the continuum at various wavelengths. The optical emission in Seyfert galaxy is delayed by a fraction of a day, and the delay increases with an increase of the wavelength up to few days in the close-infrared, and several days in the infrared. If the object becomes brighter in the optical/ultraviolet band, the spectrum becomes harder (bluer) so the variability amplitude is decreasing towards the infrared. A correlated increase/decrease in luminosity is also seen in the X-ray band but the time delays in the X-ray band itself are very short, frequently consistent with zero. Those statements are true in the statistical sense, but the agreement is not always perfect. Sometimes a sudden brightening in optical band is not accompanied by the brightening in the X-ray band, and vice versa.

Short time scales in X-ray band and the correlation with the optical emission is sometimes used as an argument that all the optical/ultraviolet variability is actually caused just by the absorption and thermalization of the variable X-ray emission. Certainly, some part of variability must be of this origin since the formation of the X-ray iron line means that indeed X-ray radiation is reprocessed by the accretion disk responsible for the optical/ultraviolet continuum. Measurements of the time delays between the X-ray continuum variation and the optical continuum variations support this view. However, it may not be the whole story since the X-ray luminosity in many objects (particularly bright quasars) may not be strong enough to cause large fluctuations of the dominating Big Blue Bump disk component. Therefore, it is likely that the disk itself also vary. However, in order to prove or disprove that we need longer multi-wavelength observational campaigns.

The problem lies in the long time scales of AGN variability. It was mentioned before that AGN vary in short time scales but there is no contradiction in these two statements. Indeed, AGN vary rapidly in a sense that variations are seen in time scales of a fraction of a day but if we wait longer we see that the observed variability amplitude increases, and the largest changes are seen in the longest time scales. If we want to understand the nature of the variability we need to know how the largest changes occur. So long lasting observations were performed but typically we never reach a saturation point in the variability amplitude. For some famous Seyfert galaxies, like NGC 4151, historical optical data have been collected on photographic plates. Such data are not of high quality, but on the other hand, long time scale variations in the optical band in this source have amplitudes reaching factor 4 to 5. Still, having the data covering the period of almost one hundred years we are not sure we already saw the highest variability amplitude! The X-ray data over such a period is not available since the first X-ray satellite detectors were launched in the sixties, and higher quality data are collected since the eighties. So far, only in one active galaxy (Akn 564) the saturation of the X-ray variability was unquestionably detected (time scales of about a year). In other well studied sources this time scale is apparently longer.

The X-ray variability is most frequently accompanied by a clear change of the X-ray spectral slope. However, in some sources, particularly those with significant absorption and/or generally steeper (softer) X-ray spectra show considerable complexity. The overall spectrum is likely to show pivoting around a certain energy (the spectrum is softer if the luminosity is higher), and additionally the variability around 1 keV is strongly enhanced as a result of the coupling of intrinsic variations with the response of the absorbing medium to the change of the nuclear flux (more ionized medium is more transparent to photons). The variability of the X-ray iron line, and the accompanying reflection component is still under vigorous discussion but most likely there is a variable component forming in the disk close to a black hole as well as a constant component, forming in the outer disk parts.

The variability is aperiodic in all energy bands. No unquestionably confirmed periodicities, or even quasi-periodicities were found so far, and the periodogram of an AGN shows a broad band activity. The power density spectra of AGN have roughly a power law shape in the doubly logarithmic diagram (log of power versus log of frequency), usually with a break if the frequency coverage is wide enough. If the break is detected, the slope of the power spectrum is about 2 above the break, and much shallower (about 1) below the break. The best determinations of the power spectra are available in the X-ray range, the power spectra in other energy bands are still rare. There is a suggestion (again, based on the single case of Akn 564) that part of the aperiodic variability can be attributed to a few components of the very broad Lorentzian type, suggesting strongly damped oscillations present in the system.

A possible exception from aperiodic behaviour of AGN may possibly be the case of OJ 287. This object seems to show repeated strong outbursts every 12 years. An interesting explanation is that we may observe there a binary black hole system in the nucleus, with a smaller black hole repeatedly crossing the accretion disk of the larger black hole during its orbital motion. The periodicity is not exact, but it can be modeled successfully when the precession of the orbit is allowed for.

The variability of typical AGN is still not understood. The variations have a stochastic character. The amplitude in long time scales is large, but the power spectra determined in short time scales and normalized with the current average luminosity are roughly stationary, or equivalently, the momentary amplitude of the variability is proportional to the current average flux. It may be understood in such way that if the source is luminous, it does not contain more emission regions of a standard size but instead each of the emitting regions is more luminous. The breaks in the power spectra have no immediate explanation, as the corresponding frequencies are roughly 10 times longer than the dynamical time scale at the last circular orbit, which either points toward a larger radius as an important location, or suggests a slower process than the orbital motion, e.g. thermal or magnetic in nature.

There are several scenarios of variability under consideration, like stochastic magnetic flares emerging above an accretion disks, shocks propagating inwards in the disk corona or in the hot inner flow, magnetic perturbations of the disk interior resulting from the local action of the dynamo and later also propagating inwards. Since we do not have deep physical understanding of these processes, the considered models are generally parametric and can be fine tuned to satisfy the data constraints like power density spectra, spectral variability, energy-dependent fractional variability amplitude, or even Fourier-resolved spectroscopy, particularly if only one of such data constraints is used.

The only issue which is well proved now is the linear dependence of the variability on the black hole mass. It is best studied in the case of X-ray variations but it seems to hold also in the optical band: optical monitoring of the Seyfert galaxy continuum requires typically at least a couple of days while quasar monitorings bring the results frequently only after several weeks since the black hole mass is usually about $10^7 M_\odot$ in Seyferts and $10^8 - 10^9 M_\odot$ in quasars. Some AGN have still smaller masses, with the record holder for now being NGC 4395 with its black hole mass of $3.6 \times 10^5 M_\odot$, and time delays between the X-ray and optical emission less than 1 hour!

3 Related objects and Unification Scheme

3.1 The “zoo” of AGN

After the discovery of quasars, astronomers begun to think that besides radio-galaxies and Seyfert galaxies, other extragalactic objects were connected with them: either because they were compact and luminous (cD galaxies), or because they had obviously a non-thermal spectrum (“Optically Violently Variable” objects - OVV, “Highly Polarized Objects” - HPO, and BL Lac objects, also named lacertides, cf. below). Some objects seeming related were starlike and blue, but did not display any emission lines in their spectrum, some others were nuclei of galaxies with emission lines, but due to atoms only once ionized (they were called LINERs or Low Ionization Nuclear Line Emission Regions), etc... We have also mentioned that two types were distinguished among Seyfert nuclei, type 1 (with broad *and* narrow lines), and type 2 (with *only* narrow lines). Other galaxies were compact with an extremely intense infrared radiation. Thus after some years, AGN were considered to take a large variety of aspects, sometimes called the “zoo” of AGN, but this richness was absolutely not understood. Why were there two types of Seyfert nuclei? Why were some

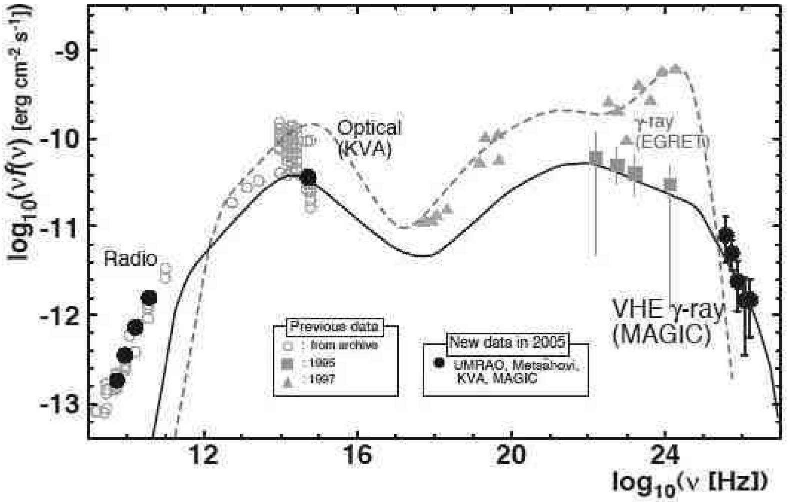

Figure 14: The Spectral Energy Distribution of the prototypal BL Lac. It shows two bumps, one in the infrared to ultraviolet range, the other in the gamma-ray range. This shape is well modeled by the Synchrotron-Self-Compton effect. One sees also the variation of the SED. After Albert et al. 2007.

quasars radio-loud and others were not? Why some radio-loud quasars were so much variable or so much polarized?

Among these objects, lacertides were probably the most intriguing. The prototype of these objects is a radio-source identified by a group of Canadian radio-astronomers as a known variable star in the Lacerta constellation, called BL Lacertae. Its spectrum is devoid of emission or absorption lines. However, some absorption lines produced by a faint nebulosity around the "star" were identified some years later, and it was thus possible to determine its redshift: BL Lacertae is an extragalactic object, whose surrounding nebulosity is simply the "host galaxy". Tens of similar objects were found. Both the intensity and the rapidity of the variability were unprecedented in extragalactic objects. During several years the absence of emission lines in these objects and their exceptional variability remained a mystery.

3.2 The "line of view" Unification: radio galaxies and radio-loud quasars, Blazars, Seyfert 1 and 2

3.2.1 Radio loud quasars and AGN: the jet and the gamma ray emission

As it can be seen in Figure 4, radio-quiet quasars do not emit much energy in the radio range, in contrast with radio-loud quasars. At the other extreme of the spectrum, radio-quiet objects do not emit beyond one MeV, while the spectrum of radio-loud objects extends to much larger energies, sometimes even up to the TeV range (10^{12}eV!). Also their spectra differ in the X-ray range, radio-loud objects being more "X-ray loud". These two properties are attributed to the presence of a relativistic jet, which is absent or weak in radio-quiet objects.

The jet is made of charged particles with relativistic random velocities, but it also has a relativistic "bulk motion". The particles produce synchrotron radiation seen as the radio emission, which can extend up to the X-ray range when the particle energy or the intensity of the magnetic field are very high. Two processes are presently proposed for the gamma-ray emission: 1. "leptonic models" where gamma-rays are produced by Inverse Compton scatterings between the relativistic electrons and either the synchrotron radio photons (it is thus called "Synchrotron-Self-Compton", or SSC), or external soft photons; 2. "hadronic models", which account for very high energy gamma-rays by synchrotron emission from hadrons, or interaction of hadrons with the ambient medium, with magnetic fields or with radiation fields. The energy of these hadrons can reach 10^{20} eV and might be the origin of the ultra-high energy cosmic rays observed recently with the Auger observatory in Argentina [4].

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[4] Hadrons and leptons are elementary particles. Hadrons are composed of quarks held together by the strong nuclear force, while leptons interact through the weak force. Basically hadrons are "heavy particles", while leptons are light particles, like electrons.

A first hint of the solution for BL Lac objects came in 1978, when Blandford and Rees proposed that their properties could be explained in terms of a relativistic jet oriented just in our line of sight. The synchrotron radiation emitted by the jet is then amplified by the relativistic bulk motion, in contrast with the "thermal radiation" (i.e. the radiation of the accretion disk and the emission lines). Moreover, owing to the amplification, any weak variation of flux becomes a dramatic phenomenon, and the amplified radiation can also be highly polarized. This interpretation gave a first evidence for the influence of the direction on the appearance of AGN. Later on, other radio-sources were identified with strongly variable extragalactic objects, occasionally displaying emission lines. The generic name "blazars" was given to this class of relativistically boosted objects, including BL Lacertae, OVV, and HPO. As an illustration, Figure 14 shows the whole Energy Spectral Distribution of the prototypal BL Lac.

Then Antonucci and Miller discovered in 1985 a way to "unify" Seyfert 1 and 2. They found broad lines in the polarized light of the famous Seyfert 2 galaxy NGC 1068. They deduced that Seyfert 2 also have broad spectral lines, but they are absorbed in some directions by a dusty torus surrounding the BLR - in a sense the prolongation of the accretion disk - and they are scattered into the line of sight, probably by a hot medium. The property of such a hot medium is to polarize the light. So, if we observe a Seyfert 1 in natural light through the torus, it will have no broad lines and will appear as a Seyfert 2, while in polarized light we will see the reflected broad lines. There are other arguments in favour of this scheme, but at the same time also some arguments against it. The region obscuring the inner regions of the nucleus was observed only recently in NGC 1068 and was found much more concentrated than predicted for the torus. Seyfert 1 and 2 seem also to differ in their starburst activity. So orientation is sure an important factor but perhaps not the only one.

Radio-galaxies were divided in two classes by Fanaroff and Riley. Class 1 radio-galaxies (FRI) are faint and are characterized by bright jets extending far from the center and decelerated during their propagation, while class 2 radio-galaxies (FRII) are powerful and have faint jets which remain relativistic all the way up to intense "hot spots" located at the end of big radio lobes (cf. Figure 1). The division between FRI and FRII depends probably on the luminosity and on the mass of the host-galaxies.

Barthel proposed in 1994 that FRIIs are actually radio-loud quasars seen through an obscuring torus, as they have strong similarities in radio morphology. If a radio-loud quasar is seen through the obscuring torus, it would indeed appear like an FRII galaxy, where the optical-ultraviolet core and the broad lines are absent or very weak. Also, the distance between the lobes would be larger and the jet weaker, as observed. This idea received several confirmations, and there is now no doubt that radio galaxies such as Cygnus A are hiding a quasar in their core.

On the other hand, FRI galaxies share common properties with BL Lac objects, like the host galaxy morphology. One can imagine that if the jet is pointed exactly towards us, a FRI galaxy would appear as a BL Lac, owing to Doppler boosting. And indeed Urry and Padovani showed that the statistical properties of FRIs and BL Lacs and of their host galaxies agree with the hypothesis of FRIs being the parent - i.e. the not relativistically boosted - population of BL Lacs. Along these lines, when a radio-loud quasar (in other words, a FRII and not a FRI galaxy) is seen exactly along the axis of the jet, it will appear as a blazar with faint broad emission lines. Figure 15 summarizes the status of the Unified Scheme.

3.3 Towards unification of radio-loud and radio-quiet objects?

The orientation with respect to the rotation axis or jet axis helped to explain the observed diversity among radio-quiet objects (Seyfert 1 vs. Seyfert 2) and radio-loud objects (radio galaxies vs. radio-loud quasars and blazars), and the two axes coincide. It still leaves us with the question, why some objects develop strong jets while other do not. This dichotomy between radio-loud and radio-quiet objects is now vigorously discussed.

Though there are numerous intermediate objects, the distribution of the radio over optical flux ratio is clearly bimodal, with a broad range of radio-loudness in radio-loud objects (the ratio can reach up to a thousand), and much more concentrated values in radio-quiet objects, with typical flux ratio around 2. Moreover, radio-loud objects are observed exclusively in elliptical galaxies, while radio-quiet ones live in spiral galaxies, at least in the relatively nearby Universe ($z \leq 1$). Finally, we have seen that Broad Absorption Lines are observed almost only in radio-quiet objects, which means that they are able to create non-collimated and relatively slow winds, while collimated relativistic jets are present only in radio-loud objects. So there is really a fundamental distinction between radio-loud and radio-quiet objects.

We do not know presently why some supermassive black holes produce preferentially jets, and others preferentially winds. Gas can be expelled from the surface of the accretion disk by radiation pressure and form a wind above the disk. This mechanism should be efficient when the ratio of the ultraviolet luminosity

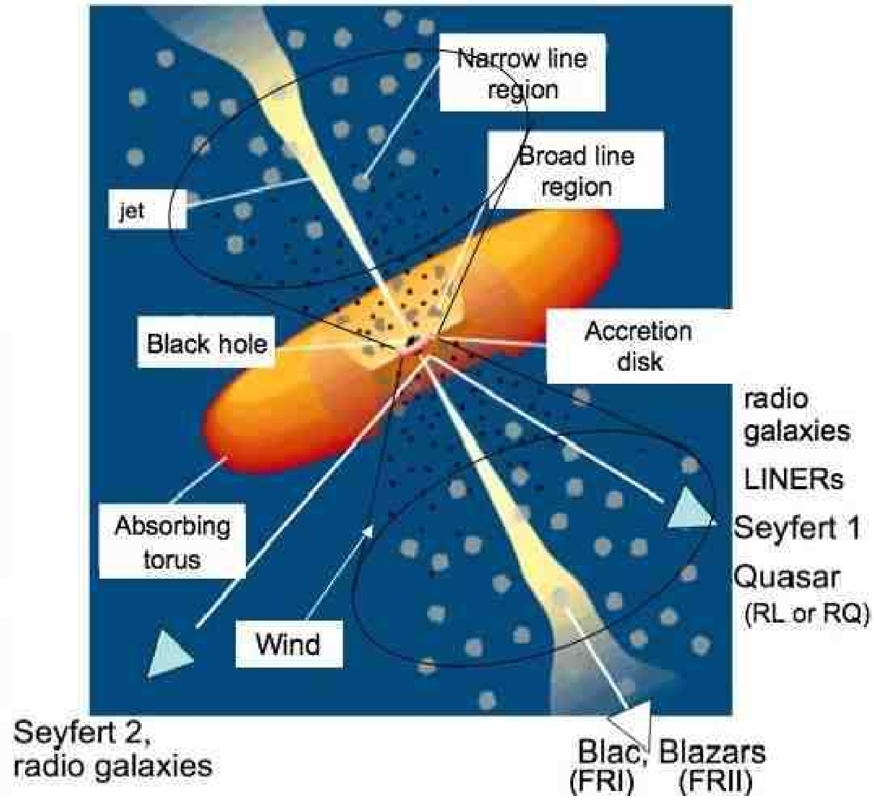

Figure 15: New Urry-Padovani figure summarizing the Unified Scheme.

to the black hole mass is high, which is the case for Seyfert nuclei and quasars. We will see below that in radio-loud AGN, the "ultraviolet bump" is less intense than in radio-quiet objects, and even sometimes completely absent. Concerning the jet, the same process can occur, but the gas could be squeezed into a narrow jet by the magnetic field of the disk. It is believed that the twisting of magnetic fields in the accretion disk collimates the outflow along the rotation axis of the central object, so when conditions are suitable, a jet will emerge from each face of the accretion disk.

Another mechanism was proposed by Blandford and Znajek to explain the jets. If a black hole rotates and is surrounded by an accretion disk with a magnetic field, the friction of the gas falling on the black hole produces electric fields. By a mechanism similar to a dynamo, rotational energy is extracted from the black hole, and ionized gas is ejected in two opposite jets in the direction of the rotation axis. With this mechanism, jets (and therefore radio-loud objects) would thus be related to the rotation of the black hole.

But why should radio-loud objects be present only in elliptical galaxies? An answer was proposed already in 1995 by Colbert and Wilson. When two spiral galaxies of similar masses merge together, the ultimate product is expected to be an elliptical galaxy. If each galaxy contains initially a nucleus with a massive black hole, the two nuclei and the two black holes will have also a good chance to merge. The new black hole will rotate very rapidly, owing to the conservation of angular momentum, like two connected skaters coming closer and turning around each other. Thus the black holes produced by this mechanism will be able to create a relativistic jet, and at the same time it will lie inside an elliptical galaxy. As we will see below, this theory is in very good agreement with our present ideas about the evolution of galaxies.

3.4 The "accretion rate" Unification: Low and High Luminosity AGN

One obvious difference between fainter AGN and quasars should be the accretion rate, i.e. the mass of gas swallowed by the black hole per unit time. A black hole radiating at its Eddington luminosity needs to swallow $\frac{L_{\rm Edd}}{\epsilon c^2} = \frac{2}{\epsilon}\frac{M({\rm BH})}{10^9 {\rm M}_\odot}$ ${\rm M}_\odot$ ${\rm yr}^{-1}$ (where ϵ is the efficiency of conversion of mass into energy) in the form of gas, without prejudice of the other forms of material, like entire stars. This accretion rate is called the "Eddington rate", and is written $\dot{M}_{\rm Edd}$. If ϵ is on the order of 10% (an average value between the maximum efficiency of a rotating and a non-rotating black hole), the Eddington accretion rate is equal to $20\frac{M({\rm BH})}{10^9 {\rm M}_\odot}$ ${\rm M}_\odot$

yr^{-1}, quite a significant amount. When the black hole has exhausted its environment, the accretion rate decreases, and so does the luminosity. Thus the gas required to fuel a quasar or a luminous AGN is not always available.

In our nearby environment, only about 15% of all galaxies are really "normal". Other galaxies manifest different degrees of "activity", even if it is not an "AGN" activity. About 40% of galaxies have a "starburst" activity, i.e. are forming stars at a high rate, particularly in their central kpc region. A few percents are "normal AGN", i.e. Seyfert 1 and 2. The rest - 40% - have a weak "AGN activity". They are called "Low Luminosity AGN" (LLAGN), but this class is very heterogeneous and difficult to identify. Some LLAGN have Seyfert-like optical spectra and an X-ray luminosity less than 10^{35} Watts, others (the already mentioned LINERs) are characterized by a very low excitation spectrum which could be due to hot stars or to shocks, and not necessarily to ultraviolet and X-ray photons from the accretion disk. LINERs are also often nuclei of massive elliptical radio-galaxies. Some LLAGN have broad lines, others have only narrow lines but broad lines are observed in their infrared spectrum (the BLR is then surrounded by a cocoon of dust absorbing all the visible radiation), etc.

Despite this complexity, it is clear that all Low Luminosity AGN share the same fundamental property as normal AGN: they contain a massive black hole. But, for some reason, the black hole accretes at a very low rate, or it is under-luminous. Actually, both ideas are correct. To understand that, it is necessary to use the accretion rate expressed in $\dot{M}_{\text{Edd}}$. Let us call it $\dot{m} = \frac{\dot{M}}{\dot{M}_{\text{Edd}}}$ and consider as an example the LINER located at the center of the radio-galaxy Virgo A (M87). It harbors a 3 $10^9 \text{M}_\odot$ black hole, and it is surrounded by a large mass of hot gas. Since one can measure the temperature and the density of this hot gas, it is possible to compute at which rate it should be accreted by the black hole. One finds about 0.1 $\text{M}_\odot$ yr^{-1}. This is a weak rate, as it is only about one hundredth of the Eddington accretion rate. On the other hand, this rate still should result in luminosity many orders of magnitudes higher than the observed luminosity of the AGN in M87, $\sim 10^{34}$ Watts, if one assumes a radiative efficiency of 10%. *So one deduces that both $\dot{m}$ is small* (0.01), *and that* $\epsilon \ll 0.1$.

In 1995, Narayan and his collaborators showed that when $\dot{m} \leq 0.01$, accretion is radiatively inefficient (in other words, $\epsilon \ll 0.1$), and a large fraction of the gravitational energy is not converted into radiation but simply disappears into the black hole (actually the suggestion was first made in 1977 by Ichimaru). The flow is indeed dilute and hot, it creates less photons, and moreover the radial gas velocity is large, so it is accreted more rapidly than it radiates. It is called an "Advection Dominated Accretion Flow" or ADAF. This theory generated intense discussions, but whatever the details of the model, one concludes that the radiative efficiency is certainly low when $\dot{m}$ is small. For instance, a way to get a small efficiency could be that most of the accretion energy is converted into the energy of the relativistic jet. Such accretion flows are called generically "Radiatively Inefficient Accretion Flow" (RIAF). The idea that Low Luminosity AGN are "anorexic" black holes with a low accretion rate and a small efficiency, is now widely accepted, and it seems that the overall spectrum of the nucleus is roughly consistent with that predicted by such flows. However, the spectrum is better modeled with the addition of synchrotron and gamma emission provided by a jet, and indeed Very Long Baseline Interferometry show the presence of a radio jet inside the nucleus of some LLAGN. It is now clear that RIAFs favor the ejection of bipolar flows, which evacuate a non-negligible fraction of the accretion energy in the form of kinetic energy. The distribution of the Eddington ratio is likely to be smooth, so the transition between bright AGN and Low Luminosity AGN may also be smooth. As was mentioned before, in some Seyfert galaxies the cold accretion disk may possibly be disrupted, albeit only in the innermost part of the flow, and we witness a transition to a RIAF.

At the other extreme, the accretion rate can be larger than the Eddington rate. This occurs easily when the mass of the black hole is relatively small. For instance a 10^6 $\text{M}_\odot$ black hole is fueled at the Eddington rate with only 0.2 $\text{M}_\odot$ yr^{-1}. What happens if more gas is available? This issue is still controversial. Some specialists think that all the gas will in fine be captured by the black hole, again with a small radiative efficiency: since the accretion flow is dense and thick, it creates a lot of photons, but they undergo many scatterings and have no time to find their way towards the exterior before the gas is accreted. Others claim that the gas is blown out before it reaches the black hole. In both cases the luminosity is Eddington limited, in contrast with the accretion rate. The truth is probably somewhere in between, as some Seyfert nuclei seem to be accreting at a rate close to Eddington, and at the same time they have strong outflows. In a sense one could say that, like gluttonous people, these black holes spit out the excess of food they cannot eat.

4 Evolution of black holes

4.1 Supermassive black holes in quasars and AGN

Quasars are a strongly evolving population. Already in the sixties it was known that the number of quasars at redshift $z = 1$ was 150 times higher than at present. Neither the black hole masses in quasars were well known at that time nor their final faith was obvious. However, black holes once formed do not disappear.

Therefore, the growth of black hole mass in the Universe could be traced using quasar activity, as proposed by Soltan in 1982. He determined the total mass of black holes locked in quasars by measuring the light of all the observed quasars, assuming that they radiate at their Eddington luminosity with a radiative efficiency of 10%. Quite extraordinarily, his result was almost correct, in spite of big approximations: a limited number of quasars was known at that time (in particular, among the distant quasars, only the most luminous), it was necessary to make a correction to get the bolometric luminosity from the luminosity observed in a given wavelength range (depending on the redshift) and this correction was badly known. Soltan found that there should be about $10^5 M_\odot$ per Mpc^3 mass accumulated in the form of supermassive black holes in our local Universe. Since the individual mass of a quasar under these hypothesis is $10^{7-8} M_\odot$, it meant that there should be 10^{-3} to 10^{-2} supermassive black holes per Mpc^3 in our local Universe. This is several orders of magnitude more than the number of quasars observed locally, and even much more than the number of all AGN in such volume.

Soltan's finding was very important. First, it showed that almost all past quasars are presently "dead", i.e. they do not radiate anymore. From the equation relating the mass and the accretion rate, one deduces that a black hole accreting at the Eddington rate grows exponentially, and doubles its mass in about 5 10^7 years when the efficiency is equal to 10%. Take for instance a luminous quasar like 3C 273. It has a mass on the order of 10^9 $M_\odot$ and a luminosity of 10^{40} Watts. If the huge amount of matter required to feed the quasar at the Eddington rate would be available during all the life of Universe, the mass reached by the black hole at the end should be 200 billions of $M_\odot$, while no black hole so massive has been detected so far. This is one of the reasons to think that quasars are short-lived, their "duty cycle" being typically 100 millions of years. After a luminous "active phase", they are lighting off and become "dead black holes" detectable only by their strong gravity field. Second, Soltan's result raised the question of "where are presently all these dead black holes?" and he suggested that they might lie in the nuclei of non-active galaxies. This is where we find them nowadays.

This conclusion was based on the presupposition that quasars are radiating close to their Eddington luminosity, with an efficiency of 10%. Nowadays, the existence of large quasar surveys and the advancement in the study of the presence of the black holes in local inactive galaxies allows to invert the original Soltan's argument in order to obtain the estimate of the average accretion efficiency. The values obtained by different research groups are all close to 0.07, only slightly higher than expected for the standard accretion disk flow onto a non-rotating black hole (0.06). This means that the simple theory is not the bad one for bright AGN. It also shows that most of the black hole mass accumulation happens in the radiatively efficient phase, or more simply speaking, watching the distant quasars now we see how the black holes grow!

4.2 Supermassive black holes in quiescent galaxies

To measure the mass of a black hole or of any other non-radiating massive object is not an easy task, unless the body is a member of a couple - like in a binary star - where one can observe the motion of one object with respect to the other. In the case of a "dead" supermassive black hole whose environment does not send any signal (except gravitational waves, but the detectors are not yet operating), the only technique is to study the matter motion around the galactic nucleus: at a given distance, the higher the velocity, the bigger the mass.

At the end of the eighties, it was possible to get rotation curves in the very centers of nearby galaxies, or simply to measure chaotic velocities at distances of only a few parsecs from the center. It led to discovery of large "black" (non-radiating) masses, up to a billion of solar masses, sitting right inside the nucleus. However, one could not be certain that these black masses were supermassive black holes: though the probability was small, the presence of massive clusters of neutron stars, for instance, was not excluded. In 1995, there were three dozens of galaxies whose "black masses" have been determined. Note that this method cannot be used for quasars or AGN, because the light of the nucleus overcomes that of the circumnuclear region.

The situation changed drastically at the moment, when it became clear that our own Galaxy had also a central massive black hole. The discovery was due to Genzel and his collaborators. In 1992, at the 3.6 m ESO NTT telescope in Chile, they had started a vast program of observations of the proper motions of stars in the Galactic Center (in the infrared, as the Galactic Center cannot be observed in the visible). The "proper motions" are displacements measured on the plane of the sky, contrary to the "Doppler motions" which are measured spectroscopically and are projections of the velocity on the line of sight. This long-term program began to give its fruits in 1995, when Genzel and collaborators were able to announce the presence of a black mass of a few millions of solar masses, in a region having a diameter less than a tenth of a light-year, spatially coincident with the well-known radio source Sagittarius A* located exactly at the dynamical center of the Galaxy. The space available for this mass was now so small that anything else than a massive black hole was improbable: a cluster of stars would rapidly coalesce and give a supermassive black hole in less than the age of the Galaxy. Thereafter, the measures were considerably refined, in particular using also Doppler velocities. Motions of stars orbiting at a few light hours from the black hole were observed, and the central black hole mass was better measured, as being 3.5 10^6 $M_\odot$. Before this discovery, the idea of a supermassive black hole in the Galactic Center was not popular, as one expected some manifestations typical of a Low Luminosity AGN, such as an intense X-ray source. Some X-ray emission from this region is indeed observed, but it is very weak compared to the accretion luminosity deduced from the material present close to the black hole, which should be trapped and accreted (on the order of 10^{-3} Eddington). Narayan thus suggested that the black hole in the Galactic Center was an "ADAF", i.e. an accreting black hole having a very small radiative efficiency. Low Luminosity AGN were also discovered in many other galaxies, and finally it was widely accepted that the accretion rate can take high or small values according to the amount of gas available close to the black hole, but that the radiative efficiency decreases suddenly when the accretion rate becomes smaller than 10^{-2} Eddington rate. As a consequence of this discovery, the status of the dark masses in inactive nuclei of galaxies was definitively set up: they are supermassive black holes.

In 1998, Magorrian and his collaborators announced that they have found a relationship between the masses of black holes in the nuclei of normal galaxies, and the luminosity of bulges of these galaxies. The "bulge" is a spheroidal region present in all galaxies except irregular ones, whose size and luminosity depends on the Hubble type: it decreases from early elliptical galaxies (which consist actually entirely of the bulge) to late type galaxies like spirals. In 2000 and later, another better relationship was found between the black hole masses and the masses of the bulges (actually the dispersion velocity in the bulge, which is directly related to its mass). It was also shown that AGN and quasars (when their host galaxy can be observed) share about the same relationship, proving that there is nothing fundamentally different between active versus quiescent nuclei of galaxies. Roughly, the bulge is thousand times more massive than the black hole (Figure16). A question remains about "intermediate" black holes, bridging the gap between stellar and supermassive black holes: do they exist in off-nuclear regions of galaxies without bulges and nuclei, i.e. irregular galaxies, or even in the centers of globular clusters?

5 Linking the growth of black holes to galaxy evolution

The black hole - bulge mass relationship observed *locally* was a great surprise, and it actually opened a new branch of extragalactic studies, linking the formation and evolution of galaxies to supermassive black holes.

Almost immediately after the discovery of quasars, cosmologists were strongly interested in the "Luminosity Function" of quasars, i.e. the luminosity radiated by quasars per unit luminosity and per unit volume of Universe (more precisely, comoving volume), at a given redshift. This domain has literally exploded these last years with the release of large X-ray, infrared, and optical surveys of AGN. Luminosity functions are presently known up to large redshifts and down to low luminosities, for all wavelength bands from radio to hard X-rays, so the whole quasar history can be reconstructed with a relatively good precision up to redshifts of 5. The number density of quasars at a given redshift can also be determined. One finds that quasars have evolved both in number and in luminosity, implying that they were as a whole both more luminous and more numerous in the past. In other words, the density evolution is luminosity dependent. Some unexpected results were also found. While the number density of quasars peaks at $z \sim 0.5 - 1$, their emissivity peaks at $z \sim 2 - 3$. It means that most of the accretion occurred at high redshifts. But on the other hand, one knows from X-ray surveys that the X-ray sky is entirely dominated by low redshift AGN, when taking into account the type 2 population which is generally missed by optical selection (because these objects are heavily obscured). It implies that the proportion of obscured AGN is much greater at small than at large redshifts. It could be due to the fact that high luminosity quasars would be less obscured than low luminosity local AGN. The question is presently not settled conclusively.

Since more than a decade, the quest for high redshift galaxies has been quite successful, and led in particular to the discovery of a population of star-forming galaxies at a redshift around 3. Precisely, the

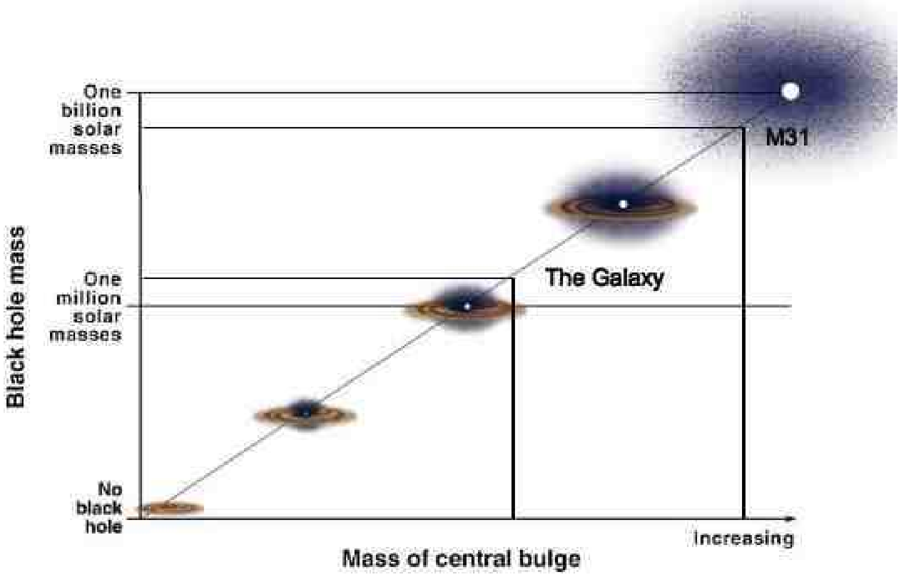

Figure 16: Scheme of the relation between M(BH) and M(bulge) showing the evolution of bulges across the Hubble types. Credit: K. Cordes & S. Brown (STScI)

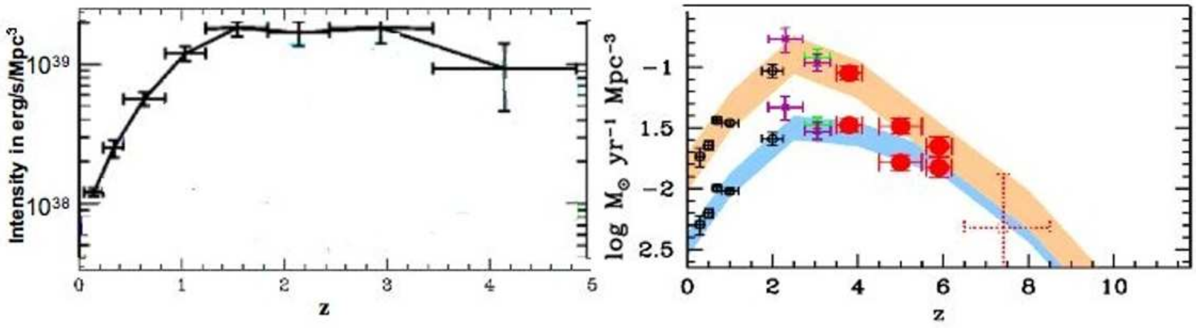

Figure 17: Evolution of quasar luminosity per unit co-volume (left), compared to the evolution of the Star Formation Rate (SFR) (right) as a function of the redshift. After Hasinger et al. 2005, and Bouwens et al. 2007. The Star Formation Rate is shown with and without a correction for the dust extinction (upper and lower points respectively).

star formation rate in galaxies peaks at $z \sim 2.5$, i.e. the same redshift as the maximum of the quasar luminosity. The history of quasars and of star formation are thus strangely similar (cf. Figure 17), though the space density of galaxies was hundred times larger than that of quasars at this time (this is due to the much shorter quasar life time). It is also well known that the star formation rate is very high in interacting galaxies. The same link was intensively looked for in quasars and other active galaxies, but they seem to be more weakly related to galaxy interactions. One thinks that the AGN activity follows an interaction with a delay on the order of 10^8 years. Since it is the typical time of an interaction, the delay breaks the relationship. Indeed numerical simulations show that an interaction between two galaxies drains material (mainly gas) towards the center of the most massive galaxy and triggers star formation. Only later, the gas begins to accumulate inside the nucleus, provided indirectly by stellar winds or directly by perturbations of the gravitational potential in the central regions. It becomes gravitationally linked to the black hole and can be accreted. All this leads to conclude that quasar activity happened early in the life of a host galaxy.

We know that the Universe consists mainly of matter which does not radiate, and is therefore "dark". Since thirty years, it is admitted by a large community of cosmologists that this matter is also "cold", and the "cold dark matter" scenario is generally adopted for the growth of structures in the early Universe (it seems now to disagree with some observations). Small fluctuations of density begin to increase under the effect of the dark matter gravity, small objects collapse first and merge to form more massive objects. This is called a "hierarchical" evolution. Curiously, quasars seem to follow an inverse, "anti-hierarchical", evolution, with quasars in the past being bigger and more luminous. Probably the peak of quasar activity occurred when the first deep potential wells of dark matter in cold dark matter models were formed, at the same time as galaxies begin to assemble in these dark matter halos. So both quasars and galaxies trace the mass function of dark matter halos in the Universe. The evolution of black holes across the Hubble time can thus be modeled with a semi-empirical method, which uses the quasar luminosity functions at different redshifts, and integrates them to describe the local evolution. This computation allows to fix different parameters of the model. In particular, since the local mass density of supermassive black holes comes from quasars, the model should be able to give locally, not only the same number of massive black holes as they were quasars in the past, but also the same mass distribution.

Although this process can account for a rough correlation between star formation and the activity of the nucleus, it does not explain why the black hole masses correlates so well with the bulge masses. This is still a matter of controversy. As already mentioned, numerical simulations show that the collision between two spiral galaxies leads to their merging and the formation of a single *elliptical galaxy*, or at least to an early type galaxy with a big bulge. During this process, the two black holes grow by accretion in each galaxy, and at the end of the merging, they have a good chance to coalesce, giving rise to a unique and spinning black hole. And indeed galaxies with two active nuclei have been discovered with the X-ray satellite Chandra. The new black hole will thus be more massive than the two initial ones, and at the same time the host galaxy will have a big bulge. However, it is not sure whether the two black holes will indeed merge or, on the contrary, one of them will be ejected from the galaxy by a "sling shot" effect. This problem will probably be solved in the near future, as gravitational waves should be emitted during the coalescence of two black holes. Detectors of gravitational waves are already operational, but at present their sensitivity is not yet high enough to detect even a single astronomical source. However, more advanced detectors are under development.

Many people also think that the black hole - bulge relationship can be explained because quasar formation has a strong impact (a "feed-back effect") on their host galaxies. When the black hole is big enough, it becomes a quasar radiating with a high luminosity, with relativistic jets and massive winds. It expels the gas from the host galaxy, shutting down star formation, heats the intergalactic gas, and stops the feeding itself. This issue is now an important subject of research.

6 Conclusions

Forty five years after their discovery, extraordinary progress in the understanding of quasars and Active Galactic Nuclei has been achieved. A most important and universally accepted idea is that the central engine is a massive black hole accreting the gas concentrated around it. However there are still many unsolved problemes. Various aspects of the inflow of the material into the black hole are not completely understood, in particular how the flow divides into a hot and a cold part, and the way they interact together. The mechanisms leading to the wind and the jet which are ubiquitous manifestations of the accretion process are not well known, neither their relative importance as compared to the accretion process itself. The origin of the emission lines is not established, for instance how the emission line regions are linked to the accretion or ejection process. The reality of the absorbing torus is questioned. The variability pattern is not well understood. A big question has still not received a definitive answer: why are there radio-quiet and radio-loud AGN, and why is it related to the nature of the host galaxy?

In the course of these studies, many unexpected discoveries have been made. The importance of the viewing angle has been put into evidence, with several important implications such as explaining the extraordinary properties of blazars, or simply the existence of several subclasses of AGN. But indubitably the most important progress is the discovery of the relation between the mass of the central black hole and the mass of the galaxy bulge. Trying to understand this relation opened the door to a completely new aspect of cosmological studies, involving large scale structure and galaxy formation and evolution, and the mutual influence that the massive black hole and the host galaxy exert on each other.

Large ground telescopes with sophisticated equipments in the optical or infrared as well as in the radio and millimeter ranges had a fundamental impact on this field, as well as spatial missions which led to the discovery of the unexpected emission properties of AGN. Big computers also helped to simulate complex problems, such as the collision or the merger of two galaxies, or the evolution of large structures. The release of large surveys of AGN in the radio, infrared, optical and X-ray ranges, begin to give their fruits. All this will be amplified in the next decades with the new generation of extremely large telescopes and interferometers, with bigger computer capabilities, and with new spatial missions. Quasar and AGN studies have still a beautiful future.

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Glossary

angular momentum density: The angular momentum density, or the angular momentum per unit mass is equal to the rotation velocity, times the distance to the center. It is an “invariant”, which means that it is conserved unless a dissipative process like radiation is acting. For a gas in Keplerian rotation at a distance R from a massive body of mass M, the rotation velocity is equal to $\sqrt{\mathrm{G}M/R}$, and therefore the angular momentum is proportional to $\sqrt{R}$. So the gas must find a way to lose angular momentum in order to come closer to the center.

comoving volume: The computations in cosmology are usually performed per unit of comoving volume, which takes into account the expansion of Universe. The given unit, like 1 Mpc^3, is normalized to our local Universe.

Comptonization: Increase of the energy of a photon due to the collision with very energetic electron. If soft (e.g. optical) photons undergo subsequent collisions in a very hot thermal plasma they finally emerge as X-ray photons, and their spectrum is of a power law shape.

Doppler effect: The wavelength of a spectral line emitted by an atom having a velocity *projected on the line of sight* V_r is shifted by an the amount $z = V_\mathrm{r}/\mathrm{c}$, where c is the velocity of light. It is shifted towards long wavelengths if the atom moves away from us, and to short wavelengths if it moves towards us. This effect was discovered by both Doppler and Fizeau, but it is generally called “Doppler effect”. If the motions of the atoms, or of “clouds” containing the atoms, are randomly distributed, the spectral lines would contain components of shorter and longer wavelengths, and the net result would be a broadening.

escape velocity: In order for a spacecraft to escape the gravitational attraction of the Earth, it should have a vertical velocity larger than the “escape velocity”, equal to $\sqrt{2\mathrm{G}M/R}$ =11 km s^{-1}, where M is the mass of the Earth, G the universal gravitational constant, and R is the Earth radius. The same relation applies at the horizon of a black hole for the light speed.

Gravitational Redshift: The gravitational redshift, also called z, is roughly equal to $\mathrm{G}M/R\mathrm{c}^2$, where G is the constant of gravitation, M the black hole mass, and R the radius of the emission region.

Ionization state of an atom: An iron atom is said to be 9 times ionized when 9 electrons have been removed from the atom. The ions - i.e. ionized atoms - have a positive electric charge, and are thus noted Fe^{+9}. But since the neutral atom is noted FeI, the lines emitted by Fe^{+9} are noted “FeX” lines. This is of course valid for all other ions.

Lyman series: The Lyman series of hydrogen corresponds to transitions between the first - ground - level of this atom and the upper levels. Lα is the transition between the first and the second level.

Nucleus: A small central region present in all galaxies except in irregular ones. It contains a dense star cluster, which lies at the dynamical center of a galaxy.

Redshift: The relative difference between the observed and the laboratory wavelength. Its relation with the distance and the travel time depends on the values of the Hubble constant, the deceleration parameter and the “cosmological” constant Λ. The largest presently observed redshifts are close to 7 and correspond to quasars having lived about one billion years after the Big Bang.

Relativistic Particles: A particle is called "highly relativistic" when its velocity differs relatively from the velocity of light only by a small factor, say 1/100 or 1/10000. The particle energy is thus equal to the product $m_0 c^2 \gamma$, where m_0 is the particle rest mass, c is the light velocity, and γ (the Lorentz factor) is equal to $1/\sqrt{1 - v^2/c^2}$, where v is the particle velocity; so γ can be much larger than unity.

Rotation Curve: The measurement of the rotation velocity for a flat circular system like a spiral galaxy projected on the line of sight (done with the use of the Doppler effect) as a function of the distance from the center.

rotation velocity: The rotation velocity is equal to the escape velocity divided by $\sqrt{2}$.

Stellar Black Hole: When a massive star has finished burning all its nuclear fuel - elements like hydrogen, helium, carbon, nitrogen, oxygen, which are able to fuse and build heavier particles while loosing some mass and therefore releasing energy - it explodes as supernovae. At the same time its inner core implodes and becomes a very compact star made of neutrons sticked together and called therefore a "neutron star". However, when the mass of the collapsing core is larger than 3 solar masses, the collapse should go on until the state of a black hole. Binary stars were discovered to radiate intensively in the X-ray range, owing to the presence of a compact star attracting the gas from its companion. Several of these compact stars were then strongly suspected to have a mass larger than 3 solar masses, and therefore to be black holes and not neutron stars.

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Bigraphical Sketches

Suzy Collin was born in Paris, France, on September 10, 1938. She made academic studies in Paris University and got a master degree in physics in 1959. She spent a third cycle thesis in 1964 and a "state doctorat" in astrophysics in 1968.

In 1960, she became assistant professor at the Paris University. She teached physics and astronomy at all levels during 13 years, and worked in "Institut d'Astrophysique de Paris". In 1973 she got a full time research job in the "Centre de la Recherche Scientifique", where she became "Directeur de Recherches" in 1974. Since 2003, she is "emeritus researcher" at the Paris-Meudon Observatory. She was the superviser of about 12 PhD thesis.

In her thesis on Seyfert galaxies, she has predicted the variability of the broad lines and shown that the emission region is photoionized. Then she tackled different subjects, in particular on the heating of interstellar matter and on the chemical abundances in HII regions and in galaxies, but she worked essentially on the physics of Active Galactic Nuclei. She focused first on the problems of the Broad Emission Line spectrum, and since about 20 years, on the accretion disc structure and emission. She has published about 150 articles in scientific journals, and 50 in popular books or journals, as well as a popular book on quasars with Grazyna Stasinska (Editions du Rocher), several lecture notes, and she has presently a book in press on the history of quasars.

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Bożena Czerny was born in Kłodzko, Poland, in 1952. She was educated in Warsaw, she has got her PhD degree at the Copernicus Astronomical Center and she works at this institute till now, since 1996 as a professor. She published about 200 papers in scientific journals, most of them aimed at modelling accretion processes onto black holes, including Active Galactic Nuclei. She is a member of the International Astronomical Union, of The International Union of Pure and Applied Physics (secretary of the Commission 19 in years 2008-2010), and of the Polish Astronomical Society.