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 of them are luminous AGN, and in about 40% galaxies, the central black hole accretes gas at a very low rate. The accretion flow has 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" (*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.*), 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, 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 billion light-years (*Actually their light has traveled during 13 millions years, but their real distance is much larger than 13 millions light years, according to the expansion of Universe.*), 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 for about 15 years beginning in 1965 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 other 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 us to see host galaxies harboring the nearest quasars.

The discovery of quasars could have been anticipated and actually *was* anticipated in the 1950s 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 II 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 $10^{54\text{-}55}$ Joules was stocked in extragalactic radio-sources, corresponding to the complete transformation of $10^{7\text{-}8}$ $M_{\odot}$ into pure energy. Burbidge thus raised immediately the question of the origin of this enormous energy. His result was largely premonitory since only thirty years later, in 1990, 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".

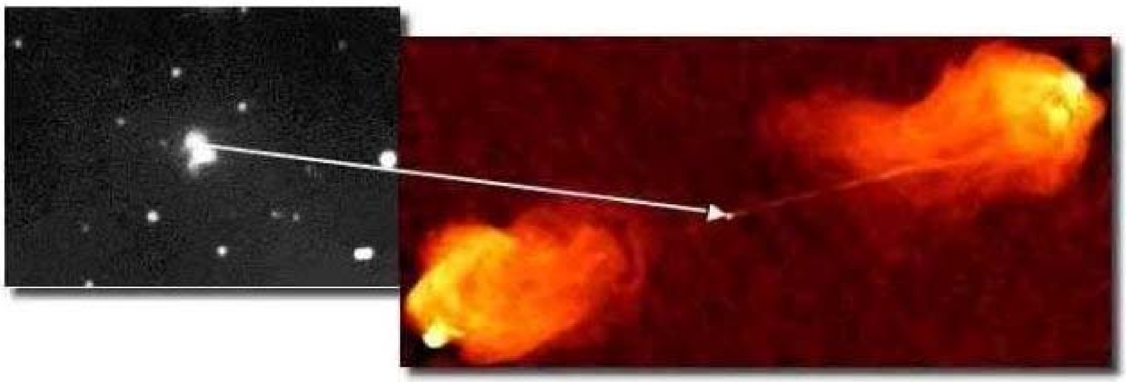

Figure 1. The radiogalaxy Cygnus A. On the left, a visible image as it was observed by Baade and Minkowski in 1954. On the right, a recent radio map of the galaxy, showing two big lobes linked to the galaxy (which is in the center) by a thin jet. Notice the "hot spots" at the extremities of the radio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

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

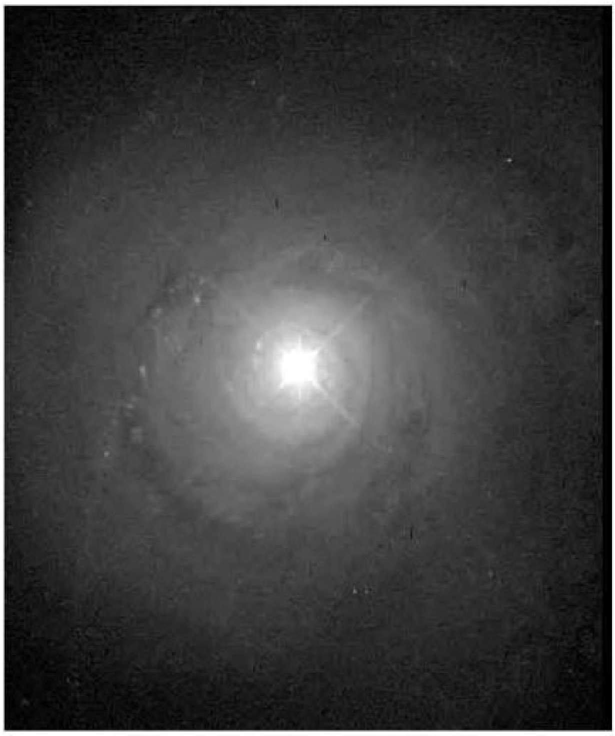

Figure 2. An image of one of the six galaxies studied by Seyfert, NGC 5548, obtained with the Hubble telescope. It shows the bright and starlike nucleus. Source: HST.

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 in the 1980s, twenty years later, when the pictures obtained with good receptors on large ground-based telescopes and on the Hubble telescope allowed us 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 1970s, 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.

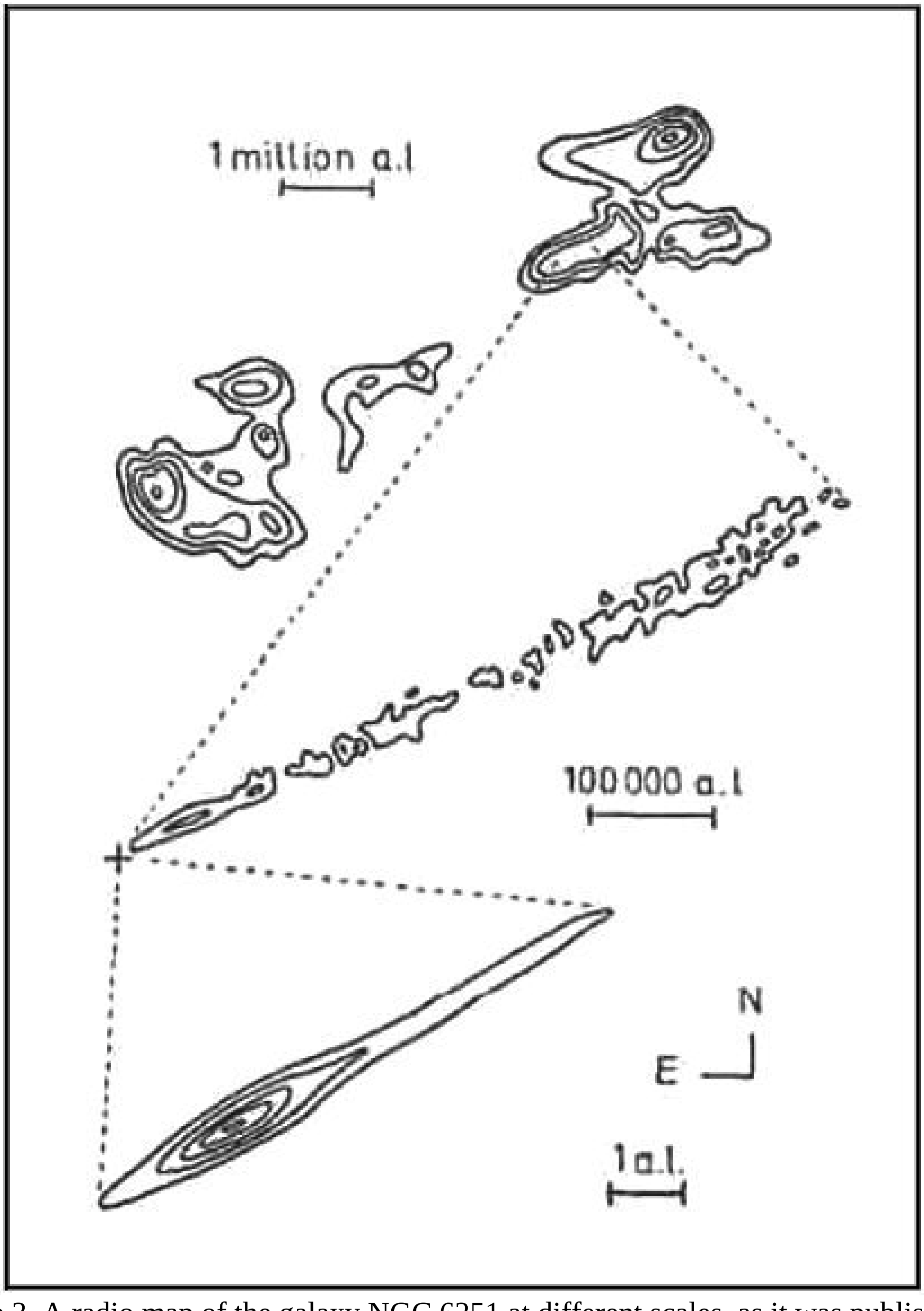

Figure 3. A radio map of the galaxy NGC 6251 at different scales, as it was published in 1978 by Readhead, Cohen and Blandford. It shows clearly that the large radio lobes are ejected by a tiny source at the position of the galactic nucleus. Courtesy Roger Blandford.

Until 1980 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 “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 began to be accepted, all the more so that neutron stars - also strange bodies whose existence was predicted already in the 1930s - 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 sentence 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.

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Biographical 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 taught 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 supervisor of about 12 PhD theses.

In her thesis on Seyfert galaxies, she has predicted the variability of the broad lines and shown that the emission region is photo-ionized. 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.

Dr. Collin is member of the International Astronomical Union, of the European Astronomical Society, of the French Physical Society, and of the French Astronomical Society, of which she was the president from 2000 to 2002.

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 modeling 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.