8. **ACTIVE GALACTIC NUCLEI. RADIO GALAXIES AND QUASARS**

This Section starts analyzing the phenomenon of extragalactic Active Galactic Nuclei. Here we will essentially discuss their low-photon-energy emissions, while in Sect. 9 we will expand on the high-photon-energy ones.

### 8.1 Active Galactic Nuclei: Generalities

We know that normal galaxies constitute the majority population of cosmic sources in the local universe. Although they may be quite massive (up to \(10^{12} M_\odot\)), they are not typically very luminous (never more luminous than \(10^{11} L_\odot \sim 10^{44} \text{ erg/sec}\)). For this reason normal galaxies have remained hardly detectable at very large cosmic distances for long time, with recent advances mostly thanks to technological observational improvements.

For several decades, since the '60, the only detectable objects at large cosmic distances belonged to a completely different class of sources, which did not derive their energy from thermonuclear burning in stars. These are the **Active Galactic Nuclei**, for which we use the acronym AGN. The galaxies hosting them are called **active galaxies**. For their luminosity, Active Galactic Nuclei and Active Galaxies have played a key role in the development of cosmology, further to the fact that they make one of the most important themes of extragalactic astrophysics and High Energy Astrophysics.

Apparently, the interest for the Active Galaxies as a population might seem modest, as in the local universe they make a small fraction of normal galaxies, as summarized in the following. There are four main categories of Active Galaxies and AGN:

1. galaxies with an excess of infrared emission and violent activity of star formation (*starburst*), selected in particular in the far-IR, the luminous (LIRG), ultra-luminous (ULIRG) and hyper-luminous (HYLIRG) galaxies: the 3 classes have bolometric luminosities \(>10^{11} L_\odot\) (LIRG), \(>10^{12} L_\odot\) (ULIRG), \(>10^{13} L_\odot\) (HYLIRG);

2. radio-quiet active nuclei (like optical quasars and Seyfert galaxies);

3. radio-bright active nuclei (like radio galaxies and radio quasars);

4. jetted active galactic nuclei (like BLAZARs, see Sect. 9).

The characteristics of these different categories, particularly those 2. and 3. above, and few mentions to the physical processes that explain this phenomenology are treated in this section.

The studies of the local luminosity functions for the different populations show that in the local universe:
a. LIRG, ULIRG and starburst galaxies make about 10% of normal galaxies;
b. radio-quiet AGN make 10% of starburst galaxies (and ~1% of normal);
c. radio-bright AGN are 10% of the radio-quiet (and 1% of the normals);
d. jetted AGNs (like BLAZARs) are about 1% of all radio-loud sources.

This holds in the local universe. But one of the results of the observational cosmology was to show that Active Galaxies have made quite a more important cosmological component in the distant past of the universe, when the radiant energy produced by them was orders of magnitude larger than today.

The present Section is dedicated to an introduction to the important topic of the AGN nuclear activity and related. This follows both an historical sequence about their discoveries (starting with radio galaxies, then optical quasars), as well as a progression in emission frequency. This Sect. considers the low-energy emission by AGNs. The next Sect. will instead cover the high-photon energy part (X and gamma). Indeed, the radio emission from radio sources has offered the first clear evidence of (large) energy generation not related to stellar activity, as discussed below.

### 8.2 Radio-emitting Active Galactic Nuclei: the Radio galaxies and their synchrotron emission

Radio galaxies, discovered by the application of techniques of radar observations developed during the II world war, have offered the first evidence of relevant non-thermal emissions by astrophysical sources and the existence of high-energy phenomena in the cosmos.

![Figure 1. Position in the sky of the first and brightest discovered radio sources.](image)
The first observations at the end of ’40s have been followed up by the first identifications during the first years of the ’50s. Baade & Minkowski (1954) identified for the first time Cygnus A\textsuperscript{1} with a distant galaxy at 250 Mpc. Later, the radio source Centaurus A has been associated to the peculiar elliptical galaxy NGC 5128, Virgo A with the super-giant galaxy M87, Perseus A with NGC 1275. The positions in the sky of these bright radiosources are indicated in Fig.1, while the radio image of a famous radiosource is shown in Fig.2.

That these emissions should be interpreted as phenomena involving non-thermal particles is indicated by the enormous values of the brightness temperature $T_B$ obtained from these observations. $T_B$ is the temperature that a black-body should have to emit with a surface brightness $I_v$:

$$T_B = \frac{c^2 I_v}{2k
u^2} \quad \text{[8.33]}$$

Ginzburg (1952) and Schlowskij (1952) have first suggested that these radio emissions are due to synchrotron radiation by ultra-relativistic electrons in a weak magnetic field.

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**Figure 2.** This image is a radio map (at a wavelength of 22 cm) of the powerful radio galaxy Cygnus A, produced from observations at the Very Large Array by John Conway and Philip Blanco in March 1994. The $2 \times 1$ arcminute image shows Cygnus A’s famous double radio lobes, spanning over 500,000 light years.

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### 8.3 Morphological and spectral properties of the radio galaxies

At low radio frequencies ($\nu<1$ GHz) enormous structures dominate the source, with 2 well separated lobes, having radio spectra of power-law shape $S_\nu \propto \nu^{-\alpha_r}$, with $\alpha_r \sim 0.75 \pm 0.2$, $\alpha_r$ being the radio spectral index (see a real example in Fig. 5b), then consistent with what is predicted by the synchrotron theory (Sect. 5.8).

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\textsuperscript{1} The names of bright radio sources are based on that of the constellation within which they were identified, followed by an alphabetic sequence as a decreasing function of their flux.
The morphologies of extended radiosources have been classified by Fanaroff and Riley:

1) Il Fanaroff-Riley di tipo-I corresponds to double radiosources with surface brightness distributions relatively smooth and decreasing towards the borders (Fig. 7), named as "relaxed doubles".

2) Il Fanaroff-Riley di tipo-II are double radiosources with surface brightness distributions with external edges at high surface brightness ("hot spots"), looking like well collimated sources (Fig. 8).

3) Peculiar radiosources, like the "head-tail" in Fig. 9, and in general with complex morphology. These peculiarities are for example due to the fact that these sources are found in clusters of galaxies: the presence of a hot plasma inside the cluster induces a head effect in the radio emission due to the motion of the host galaxy inside the cluster.

Figure 7.
Isophotal radio contours of the radiogalaxy Centaurus A. The image in the square is an enlargement of the optical counterpart that is in the center of the system, and corresponding to the galaxy NGC5128.

Figure 8.
Isophotal radio contours of the radiogalaxy Cygnus A (see radio image in Fig. 2).
The sizes of extended radio sources vary according to the source radio luminosity. At low redshifts, typical sizes are about 100 to a few 100 Kpc, corresponding to low-luminosity objects. More luminous objects typically found at high redshifts have sizes of about 1 Mpc (a high redshift radiogalaxy has been observed to have a size of 2.4 Mpc!).

Figure 9. Map at 5 GHz with the Westerbork radio telescope of the radio source head-tail 3C85.1B (associated to the galaxy NGC 1265), in the Perseus cluster. DX: enlargement of the compact radio source.
**Figure 10.** Radio image of Cignus A with VLA, showing a radio jet linking the extended radio volumes and the central source.

**Figure 11.** The radio source associated with NGC 6251, observed with various radio telescopes with different angular resolutions, including VLBI for the smallest scales.

It is shown the extraordinary collimation of the jet to be maintained on a scale of 1 Mpc!
The optical galaxy counterpart of the radiosource is typically situated at the center of a line connecting the two radio volumes. Often the radio volumes are related to a compact radio source by narrow radio bridges, named jets. Some of these are shown in Figures 9 and 10. In almost all cases close to the centre of these galaxies there are compact radio emissions. These compact components show relatively flat radio spectra, with radio spectral indices $\alpha_r<0.5$, and sometimes inverted spectra ($\alpha_r<0$).

Note that, in the case of radio galaxies and different from what happens for Seyfert galaxies as discussed below, the host galaxy turns out to be an early-type galaxy, that is an elliptical or S0 galaxy.

The flat spectra, in turn, are of two kinds: 

- **a)** spectra really flat and power-law shape (corresponding to low values of the energy spectral index, $p \sim 1$) are in particular associated to some categories of radiosources, the BL-Lac, or BLAZARs;
- **b)** spectra with multi-components, with evidences of self-absorption in systems of clouds emitting synchrotron with different particle densities (hence different radio optical depth). In this case we have spectra overall flat, but with many components.

Observations based on the technique of radio imaging named Very Large Baseline Interferometry (VLBI) of the compact nuclear components have been performed with angular resolution down to millionths of arcsec, possible thanks to the very high surface brightness of these objects. It has been verified that on the smallest angular scales the same jet-like structures observed on the largest scales are found (Fig. 11). The interpretation is that there should be a kind of "guns" inside the nucleus of these objects able to produce jets of plasma, particles and radiation extremely well collimated, able to transfer energy from the central source to the extended radio-volumes.

### 8.4 Energetics of the synchrotron emission by radio galaxies

Taking advantage of the relatively simple physics ruling the emission by the extended radio-volumes in radio galaxies, it is interesting now to investigate the amount of energy contained and possible origins of this. Let us assume that the source consists in a volume $V$ with chaotic magnetic field of average intensity $B$, within which there is a flux of relativistic electrons of density $N(\varepsilon) = K \varepsilon^{-p}$ between $\varepsilon_1$ and $\varepsilon_2$. The total contained energy will be given by the sum of those of various components:

$$E_{tot} = E_e + E_p + E_{mag}$$

Let us start to analyse the first term, the electron contribution, the easiest to estimate:

$$E_e = V \int K \varepsilon^{-p} \varepsilon d\varepsilon = \frac{VK}{2-p} \left[ \varepsilon_2^{2-p} - \varepsilon_1^{2-p} \right].$$
Let us express now the product $VK$, that we do not know a-priori, in terms of the emitted synchrotron power, a measurable quantity. From [8.4], considering that for every electron we have $ɛ = γmc^2$, we can write for the emitted power:

$$P = \frac{4}{3}σ_T c β^2 γ^2 U_B = AB^2 ɛ^2$$

with $A$ an irrelevant constant. We can now express the total radio luminosity $L$ as an integration of [12.4]:

$$L = V \int_{ε_i}^{ε_f} K ɛ^{-p} P_ɛ dɛ = \frac{A VK B^2}{3 - p} \left[ ɛ_2^{3-p} - ɛ_1^{3-p} \right]$$

such that

$$E_{el} = \frac{1}{A} \frac{L}{B^2} \left[ ɛ_2^{2-p} - ɛ_1^{2-p} \right]$$

In fact we do not know the cutoff energies of electrons $ɛ_1$ ed $ɛ_2$, but instead the cutoff frequencies $ν_1$ e $ν_2$ of the spectrum. From [12.3] we can write

$$ν = γ^2 qB / mc \quad => \quad ɛ = D \frac{ν^{1/2}}{B^{1/2}}$$

$$E_{el} = \frac{1}{AD} \frac{L}{B^{3/2}} \left[ ν_2^{α+1/2} - ν_1^{α+1/2} \right]$$

where $D$ makes a second constant of mere normalization. We need now to evaluate the contribution of protons to energy, $E_p$, a more difficult task. To keep charge neutrality, for any electron a proton should be accelerated, otherwise enormous electric fields would be generated to attract particles of opposite charge and re-balance the charge distribution. However, although the number of particles is maintained, their energy could be very different (for all ultra-relativistic particles the velocity is in any case about $c$). Electrostatic accelerations (pure $E$ fields) would give energies independent of the mass: $d(γmc^2)/dt = eE \times v$. Other mechanisms would instead tend to favour the larger masses (the protons): among these the acceleration mechanism proposed by Fermi, as shown in Sect. 7. Then we expect that $E_{el}/E_p < 1$. In the cosmic rays we effectively measure $E_{el}/E_p \sim 1/100$ (see Sect. 5.4 and Sect. 7). Let us thus define:

$$a = \left( \frac{E_{el}}{E_p} \right)^{-1} \approx 100$$

Then, including in the constant $Q$ the various factors multiplying $L/B^{3/2}$, we will have:

$$E_{tot} = (1 + a)E_{el} + E_{mag} = Q(1 + a) \frac{L}{B^{3/2}} + \frac{VB^2}{8π}, \quad [8.38]$$

a behavior which is illustrated in Fig. 12.
It is clear that there will be a value of $B$ for which $E_{\text{tot}}$ is minimal, that can be obtained by making the derivation of [8.38] as a function of $B$:

$$B^* = \left[ \frac{6\pi Q(1+a)L}{V} \right]^{2/7} = \left( \frac{9}{2} \right)^{2/7} \frac{[Q(1+a)L]^{2/7}}{l^{6/7}}$$

with $l$ the linear dimension of the radiosource (assumed to be spherical). The minimum energy corresponding to $B^*$ is therefore:

$$E_{\text{min}} = \frac{Q^{4/7}}{8\pi} l^{9/7} (1+a)^{4/7} L^{4/7} \approx 10^{42} \nu_{\text{min}}^{2/7} l^{9/7} (1+a)^{4/7} L_{42}^{4/7} \text{ [erg / s]} \quad [8.39]$$

where $\nu_{\text{min}}$ is the cutoff frequency of the observed spectrum in Hz, $l$ in Mpc, $L$ expressed in $10^{42}$ erg/s. It is clear from Fig. 12 that the quantity $B^*$ is very close to the value of the $B$ field for which there is **equipartition of the energies** in the magnetic field and in the particles: a simple calculation shows that at the value of $B^*$, we have $E_{\text{mag}} = 3/4 E_{\text{part}}$.

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**Figure 12.** The behaviour of the total energy as a function of the magnetic B field intensity.

We have then obtained a double result: *(a)* we have evaluated a reference value for the magnetic field $B$ that has a particular meaning, that is to be very close to that for which we have energy equipartition; *(b)* we have estimated the minimum possible energy for the radiosource. $B^*$ does not have the meaning of a precise measurement, because we do not know if the source is in a state of real energetic equipartition of its various components. In particular there are evidences that in compact radiosources close to the primary nuclear energy engine, this condition is not verified. However, at least in the extended components of radiosources (inside which it is quite plausible that all physical processes happen on relatively longer timescales than in compact
radiosources), $B^*$ makes a very useful reference value. Concerning now point (b), we note that $E_{\text{min}}$ is minimal both in mathematical sense, and because, if the lower cutoff of radio spectrum is not observed (e.g. if it is lower than the ionospheric limiting frequency, 30 MHz), part of the spectrum is not observable.

<table>
<thead>
<tr>
<th>Object</th>
<th>redshift</th>
<th>$M_{\text{pg}}$</th>
<th>Size (diam. x sep.) in kpc</th>
<th>$\log L$ (erg/s)</th>
<th>$\log E_{\text{min}}$ (erg)</th>
<th>$\log B$ (Gauss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centauro A</td>
<td>0.003</td>
<td>-21.3</td>
<td>120 x 240</td>
<td>41.8</td>
<td>59.3</td>
<td>-5.3</td>
</tr>
<tr>
<td>Cigno A</td>
<td>0.057</td>
<td>-21.2</td>
<td>17 x 100</td>
<td>44.8</td>
<td>60.0</td>
<td>-5.5</td>
</tr>
<tr>
<td>3C 33</td>
<td>0.05</td>
<td>-20.9</td>
<td>10 x 200</td>
<td>42.8</td>
<td>58.6</td>
<td>-4.0</td>
</tr>
<tr>
<td>3C 219</td>
<td>0.175</td>
<td>-19.6</td>
<td>60 x 260</td>
<td>45.3</td>
<td>59.9</td>
<td>-4.3</td>
</tr>
<tr>
<td>3C 295</td>
<td>0.461</td>
<td>-20.1</td>
<td>5 x 15</td>
<td>45.0</td>
<td>59.5</td>
<td>-5.3</td>
</tr>
</tbody>
</table>

It is interesting that for radio sources at low redshifts, for which the analysis has been performed in good detail, $E_{\text{min}}$ assumes values already quite high. The above table shows values of the equipartition field and of the minimum energy calculated by assuming $a=100$.

From a comparison of $E_{\text{min}}$ and $L$ we can directly infer the lifetimes of the sources to run from $10^6$ years (for the most powerful like Cygnus A, $L=10^{45}$ erg/s), up to $10^8$ years (for the weakest, with $L<10^{42}$ erg/s). An estimate of the lifetime can be obtained very simply from the ratio of the bolometric radio luminosity $L$ to the total energy content of the components:

$$t = \frac{E_{\text{min}}}{L}.$$

### 8.5 An Heuristic Model for Nuclear Activity

To better understand the meaning of this estimate of the energetics, let us convert it in mass from the relation $E=mc^2$, for which $10^{60}$ erg of contained energy correspond to the conversion of $10^6 M_\odot$ in energy of relativistic particles of at least 1000 MeV in timescales of $10^6$ years. 1000 MeV per particle are required by the fact that we need photons of $\nu \sim 10^9$ Hz within magnetic fields of $B \sim 10^{-5}$ Gauss: from $\nu = \gamma^2 eB/mc$ we have that $\gamma \sim 1000$ is required (while the rest energy of the $e^-$ is 511 KeV).

It is entirely implausible that stellar processes are responsible. We know (from Cosmology III year course) that at most $10^{-2} - 10^{-3} M_\odot$ is transformed in energy by thermonuclear reactions in stars, and in addition this energy is emitted in form of
particles of a few MeV. To obtain particles of 1000 MeV would require a very low thermodynamic efficiency. All this would imply that entire galactic masses (>10^{10} M_{\odot}) would annihilate in the nuclei of galaxies on very short timescales (10^6 years). There is no evidence that this never happened, instead dynamical studies of stellar motions in the nuclei with HST (the STIS spectrograph) have shown that there are no more than a few 10^9 M_{\odot} of matter in the nuclei in the form of compact stellar clusters or collapsed objects (likely super-massive black holes).

Other processes are evidently required to explain the phenomenon, the most plausible one considers the conversion of gravitational energy \( E \sim GM^2/R \) of a massive system into rotational energy \( E \sim J^2/R^2 = I \alpha^2/2 \), where \( \alpha = v/R \) and \( I = \sum m_i r_i^2 \sim (MR)^2 \) is the inertial moment of the rotational system) and from rotational energy to energy of accelerated particles and electromagnetic fields.

The first conversion, from gravitational to rotational, can happen with a very high efficiency, of order of 10%. Indeed, in the collapse down to a few Schwarzschild radii \( (R_S = 2GM/c^2) \), radius at which the escape velocity from the object corresponds to the light velocity) we have:

\[
E_{\text{tot}} = \frac{GM^2}{5R_S} = \frac{GM^2 c^2}{5 \cdot 2 \cdot GM} = \frac{Mc^2}{10}.
\]
Note that $5R_S \sim 10$ Km for a star of solar mass, and this is roughly the radius of a neutron star.

This last stable orbit of 5 Schwarzschild radii refers to a non-rotating object. The situation changes for rapidly rotating collapsed objects. In particular, the efficiency of mass energy conversion can attain a limiting value of 42\% efficiency for plasma accreting onto a maximally rotating black hole along orbits in the same sense of the spinning black hole.

As for the second conversion, from \textbf{rotational energy to radiation}, it is interesting to use, to evaluate the efficiency, an analogy with processes taking place within a galactic source of great physical and astrophysical interest: the pulsating neutron star \textit{(pulsar)} present in the centre of the Crab Nebula and discussed in Sect. 5.11. There are evidences that the generation of energy through particle acceleration happens in this source with an efficiency close to 100\%: if $I\omega^2/2$ is the rotational energy of the pulsar, we can determine its temporal variation as

$$\frac{d}{dt} I\omega^2 = I\omega \dot{\omega}.$$  

From measurements of the rotational speed $\omega$ with observations of the pulsed light in the optical and radio, we get $\omega=33$ milliseconds. In addition observations on a decadal baseline of the pulsar can determine the time derivative $\dot{\omega} = d\omega / dt$ with high precision. We can also say to known a reliable value for the momentum of inertia $I$, based on models of the structure of the neutron star, that turns out to be $I=10^{45}$ g cm$^2$. We finally get

$$\frac{d}{dt} I\omega^2 \approx 2 \times 10^{38} \text{ erg/s}. \quad \text{[8.40]}$$

This estimate can be compared directly with the total bolometric luminosity of the nebula, easily achievable by integration of broad-band spectra of the object (having a broken power-law spectrum from radio to the gamma rays, with a first steepening at about $10^{13}$ Hz (see Sect. 5.10.2). The bolometric luminosity results to be $L_{\text{bol}} \sim 10^{38}$ erg/s, about half our estimate of the rate of energy loss by the pulsar in [8.40].

It is interesting to note that there are decisive evidences of the presence, in the nuclei of active galaxies and quasars, of collapsed structures of large mass (likely supermassive black holes, with estimated masses from $10^7$ up to $10^{10} M_\odot$). These collapsed supermassive structures are interpreted as the analogue on large scales of the neutron star in the Crab. On physical/dynamical grounds, \textit{collapsed objects of such a mass can only be super-massive black holes} (SMBH).

We conclude that there is an already well-established scenario explaining with the presence of such supermassive collapsed objects all the phenomenology of Active Galactic Nuclei (AGN). A very attractive aspect of this idea is that objects of this kind, if indeed including high angular momentum, can naturally explain:

2 Note that the black-hole is the only stable physical configuration for such large masses and mass densities.
1. the extreme observed energetics with very high efficiency of mass→energy transformation
2. the high variability and short time-scales observed in many AGN
3. the extreme directionality shown by radio jets, related with the angular momentum of the object, eventually also in association with a magnetic field.

8.6 Radio-Quiet Active Galactic Nuclei: Quasars and Seyfert galaxies

Our analysis of the phenomenon of radio galaxies in the previous subsection has been the occasion of bringing into light a fundamental astrophysical process of energy generation by gravitational collapse of gas onto supermassive compact objects. However, radio galaxies make a very small minority, from both the statistical and energetic point of view, of the whole class of Active Galactic Nuclei. The most relevant AGN population is that of the so-called radio-quiet objects.

Quasars observed with HST (Bahcall & Disney)
Figure 15. Wide-band spectral properties of Active Galactic Nuclei from radio to X-and gamma-rays [from Wilkes & Elvis 1994]. Note the average spectral slope of the sub-millimetre emission that is indicated: this is steeper in frequency than the value of $\propto \nu^{2.5}$ that would be required for self-absorption if the emission from $\nu = 10^{11}$ to $\nu = 10^{14}$ Hz would be due to synchrotron emission. Only dust emission from a dust torus in that frequency range would be consistent with the observed spectral slope.

The broad-band spectral properties of AGN are schematically illustrated in Figure 15. The spectra are similar between radio-loud (the previously discussed radio galaxies) and radio-quiet AGNs, as we see, except concerning the radio emission, that in radio-quiet objects becomes almost negligible.

This latter population includes essentially the optical quasars and the Seyfert galaxies, whose main characteristics are hereby summarized (see figures of their optical appearance). They have the following common properties:

- an intense and spatially un-resolved (point-like) emission in the optical;
- the emission presents an excess in the thermal infrared and in X-rays, and sometimes in the UV, in the form of power-law spectra;
- the optical emission, and particularly the X-rays, manifest variability of the flux as a function of time;
- in the optical spectra, intense emission lines show up, lines that are often strongly broadened (from $\sim 1000$ to several thousand Km/sec);
- the radio emission of these objects is typically very weak, and in addition the radio and optical emissions do not appear significantly correlated in Active
Galactic Nuclei, in the sense that radio-bright objects are not particularly luminous in optical, vice versa bright optical quasars are weak in radio.

*Optical multicolour image of the proto-typical Seyfert-I galaxy, NGC 4151 (image from SDSS)*

*Optical multicolour HST image showing the quasar 0157-001 and its host galaxy. The morphology of the latter is barely identifiable.*
The main difference between optical quasars and Seyfert galaxies comes from the nuclear luminosity: in quasars, it is so large that the host galaxy is practically invisible, while in Seyfert galaxies the nuclear luminosity is sufficiently low that the host galaxy (typically a spiral galaxy) is well visible (see the image of the Seyfert galaxy NGC 4151). Except for this property of the nuclear luminosity, all other characteristics are in common between quasars and Seyfert galaxies, including the luminosity functions that are contiguous in the two categories (Seyfert galaxies occupy the lower luminosity part, quasars the high luminosity part, but the two are perfectly consistent with each other in the overlapping region).

Figure 14a. Average optical spectrum of a representative sample of quasars over a large redshift interval.

The optical spectra of AGN present remarkable properties that demonstrate the different nature of these objects with respect to the normal galaxies. Figure 14a, showing the average spectrum of a number of high redshift quasars, reveals very intense emission lines, in particular permitted lines of the Balmer series of the hydrogen \(^5\). These lines are not only intense, but they also appear much broadened, with values of the line full-width at zero intensity of many thousands Km/sec. For comparison, emission lines observed in galaxies do not show widths larger than 200-300 Km/sec, corresponding to the typical motions of the stars and of the interstellar medium in galaxies and consistent with the average gravitational field in

---

\(^5\) Let us remember that in spectroscopy we distinguish forbidden and permitted transitions, that in AGN astrophysics are sometimes associated to broad and narrow lines. Forbidden lines are those produced by very low density gas (with respect to the densities that can be obtained in the laboratory), and are indicated in squared parenthesis. The permitted lines instead are those produced by gas at medium-high densities.
Evidently the emission lines in AGN are produced in galactic regions characterized by extremely high velocities and more intense gravitational fields. This fact is consistent with the idea, already expressed for radio galaxies – but apparently valid for AGNs in general – that nuclear activity is due to gas accretion onto a supermassive black-hole. This object would so generate a very intense gravitational field, that would explain the permitted line widths, assuming that they originate from dense gas in motion in the proximity of the black-hole.

**Figure 14b.** Comparison of the average spectra of a representative sample of type-I AGNs with broad forbidden lines with the average spectrum of type-II AGNs, showing both narrow and broad permitted lines.

Many permitted lines from heavy elements are evident in the spectra, like carbon, magnesium, oxygen, etc. There is also the presence of narrow lines (<1000 Km/sec) from forbidden transitions (see for example that from [OIII] and NIII]).
We have also observed AGNs, both quasars and Seyfert galaxies, with no broad emission lines and without the intense UV flux, and instead showing intense narrow emission lines in their optical spectra, with line widths of $\leq 2000$ Km/sec. They are the so called type-II AGNs, to be distinguished from the type-I AGNs that are those previously discussed with broad lines. Characteristic spectra of type-II AGN are shown in Figure 14b. Although they are more difficult to be identified and distinguished from normal galaxies, due to the lack of broad lines and weakness of the UV-optical nuclear continuum, it comes out from dedicated studies that in fact type-II objects include the majority of all AGNs.

Figure 15. Schemes representing the unified model of AGN. The upper fig. shows the torus of gas and dust seen from the top with the polar aperture, that is occupied by a low-density medium; the figure also shows that characteristic sizes of the torus. The lower figure represents, for a polar section of the torus, schematically the two line-of-sights to the nucleus, A is that corresponding to a type-I AGN, B to a type-II AGN.
The first evidence that the difference between type-I and type-II AGNs is due to a dusty toroidal structure surrounding the nuclear source comes from observations of the linear polarized radiation spectrum in the optical. This is shown in the above figure. When observed in polarized light, the spectrum of a type-II object resembles closely that of a type-I. The geometrical situation is illustrated in Fig. 15: the source line-of-sight is as segment B, but significant part of the line emission in the direction A is scattered towards the observer by material (free electrons essentially) present in the polar region of the AGN. Scattering induces linear polarization in the observed spectrum.

This effect is directly evident in the image taken with a narrow filter in Fig. 17 below, a filter centred onto a narrow forbidden line.

Figure showing the total light spectrum on top and polarized flux on the bottom for the Narrow Line Radio Galaxy and shows the first hidden Quasar, 3CR 234. The polarization angle relative to the radio axis shows that photons can only stream out of the nucleus in the polar directions. The polarized flux (akin to scattered light) spectrum shows the hidden Quasar features at good contrast. (In this case, however, the scattered ray is itself reddened.)
8.7 The AGN Unification Model

In our interpretative scheme of the AGN phenomenon, how could we understand the type-II objects, that may look like active galactic nuclei without spectroscopic evidence of a nuclear collapsed object? A likely answer comes from the so-called unified model of the nuclear activity: the model foresees that in the circum-nuclear zone gas and dust that are accreting onto the black-hole are organized in a structure with the generic shape of a torus around the nucleus, a structure presenting a hole in two polar zones corresponding to the rotation axis of the whole system. This structure, denominated accretion torus, would indeed be determined by the presence of angular momentum in the accreting gas, a momentum allowing the collapse of the gaseous in the equatorial plane (see the scheme in Figure 15).

![Diagram of the AGN Unification Model]

**Figure 16a.** Left: radio VLA image of Cygnus A. Right: a scheme representing the inner Kpc-scale region of the object with its various components, in particular the circum-nuclear torus.

The unification model foresees that type-I AGNs correspond to toroidal structures seen by the observer from a polar direction that does not intercept the dusty torus, while for type-II objects the torus intersects the line-of-sight. In this second case, the
dust present in the torus obscures both the emission of the UV continuum and the broad lines emitted by the nuclear clouds contained inside the torus and responsible for the Broad Emission Lines (see Sect. 4.7.4 for further relevant considerations about the unified model).

Let us then summarize in Figures 16 the structures of the inner regions of AGNs. The left panel in Fig. 16a shows a radio image of a radio galaxy reaching a size of 1 Mpc. The right panel shows an enlargement of the inner Kpc representing the scales characteristic of the outer dust torus edge (up to a few hundreds of parsec, possibly connected with the gaseous disc of the host galaxy). On its inner edge, the dust torus borders an accretion disc, through which gas accretes onto the nuclear black-hole. Fig. 16b makes a zoom on the main components that are believed to be present in the inner dust torus. What is clearly shown here is the region of broad emission line clouds inside the torus and surrounding the accretion disk, as well as the wide region of the narrow emission line clouds outside the torus. Further discussion concerning all these components will be done in Sect. 8.8 and 8.9 below.

**Figure 16b.** Another scheme representing the type-I and type-II lines of sight to AGNs.
An important consequence of the AGN unification model concerns the origin of the X-ray background. As discussed in the Course of *Observational Cosmology*, the combination of the optically thin X-ray emission by type-I AGNs with the low-X-ray-energy photo-electrically absorbed type-I AGNs is what is required to explain the spectral shape and intensity of the background.

### 8.8 AGN emission line systems, the Broad Line Region (BLR), and Narrow Line Region (NLR)

It is important to mention (while this topic would require quite more discussion and analysis, done in other courses) the question of the astrophysical origin of the emission line systems in AGNs.

In Sect. 8.6 we have seen that the broad emission lines typically belong to the class of "permitted" lines (meaning they come from atomic transitions that can be observed in laboratory, like the hydrogen Balmer lines, because they are produced in relatively high density media). Instead the narrow emission lines are observed to be both "permitted" and "forbidden" lines, the latter originating in low density environments that cannot be duplicated in laboratory. An example of the latter is the [OIII] line, already mentioned and visible in Fig. 14a.

![Figure 17](image-url)  
*Figure 17.* Images of NGC5728. Left: a large-scale image showing the disk galaxy; right: an HST image of its central region taken through a filter with a small bandwidth (narrow-band filter) centered on a forbidden narrow emission line. This image shows the spatially resolved NLR.
How can we interpret these different phenomenologies? The critical aspect are the high velocities of the high-density medium producing the permitted lines. These come from gas with densities $n_e > 10^8$ particles per cubic centimetre. At the same time, the broad line of CIII] at 1909 $\AA$ requires that the density should be $n_e < 10^{10} \text{cm}^{-3}$. All this can be interpreted with the presence of a system of high-density clouds in the vicinity of the black-hole, experiencing its enormous gravitational attraction. This cloud system is called the Broad Line Region (BLR). Exploiting the high variability of the continuum and measuring the time-delay with variations of these line fluxes, it is possible to infer the typical size for the BLR of a parsec or less. Since the emission per unit mass in the recombination lines is proportional to the electron density, the total mass inferred for the BLR is small, of the order of $100 M_\odot$.

The cloud system responsible for the narrow lines has opposite characteristics. The electron densities should be of the order of $n_e \approx 10^{3-4} \text{cm}^{-3}$ for these lines to be produced (this is a too low gas density to reproduce in laboratory). Because of the low inferred velocity field and lack of line intensity variability, the responsible clouds system (the Narrow Line Region, NLR) should be quite further apart compared to the nucleus, on scales that range up to a few Kpc and essentially cover the entire galaxy hosting the AGN. Interesting also to note that in some cases the NLR shows to narrow band imaging a cone-like structure (see Fig. 17) that is easily interpreted by considering that these clouds are directly illuminated by the ionizing flux from the nucleus only in directions not covered by the dusty molecular torus.

### 8.9 An evolutionary scheme for nuclear activity in galaxies

To conclude, a fundamental aspect of the AGN phenomenon, even more central than the dualism of type-I and type-II AGNs, concerns the differentiation between the radio-loud and radio-quiet objects, that is certainly not a simple orientation effect, since the extended radio-lobe emission is completely isotropic and cannot be absorbed by specific orientations. This question concerns more deeply the phenomenon of galactic activity.

A guideline for its interpretation can be achieved by considering the extreme directionality of the energy emission in radio-loud AGNs, the’ so called’ two-sided jets in the form of ultra-relativistic particles, magnetic fields, electromagnetic waves and also kinetic and mechanical energy. Such an extreme directionality is not

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4 Note that the high density implies recombination times very short, and the BLR reacting promptly to continuum variations.
observed, or it is much less evident, in the radio-quiet objects. The only likely way to understand this is to assume it to be related to the angular momentum of a nuclear supermassive and fast-rotating structure (the nuclear black-hole). In a deep analogy with what discussed for the energy emission from the Crab nebula and the Crab pulsar, it appears natural to interpret the radio phenomenon as the product of the transformation of rotational energy of the collapsed object in particle energy, trough for example a Faraday mechanism in the presence of a strong magnetic field.

So why does this collimated emission not show up in radio-quiet AGNs? Radio-quiet AGNs and quasars have certainly a hot accretion disc responsible for the big-blue-bump as discussed later in Sects. 9 and 10, hence they should also contain a central massive black-hole, but likely not a super-rotating one.

A possible interpretation of the overall AGN phenomenology could then be obtained in the framework of an evolutionary scheme of nuclear activity in galaxies. Let us start by considering this activity as following a transient process of rapid transfer of gas and dust to the inner regions of the galaxy. Such rapid gas flow may be caused by galaxy interactions or mergers, or by other instabilities in the gaseous disc in spiral galaxies. This gas inflow would first produce an intense star formation in the circum-nuclear regions, leading in essence to the typology (1) [starbursts, LIRGs, ULIRGs] of AGNs in the population scheme described in Sect. 8.1.

A fraction of the accreted gas in the galaxy nucleus would reach the very inner regions and go to accrete onto the black-hole, so activating the quasar. How in detail does this ultimate infall of gas happens is still quite unclear, but certainly the accreting material needs to loose most of its angular momentum to achieve it (see Sect. 10 for all details). These firstly activated quasars are expected to show concomitant activity of star formation and gravitational AGN accretion. We know that there is a well-known class of similar objects in at least a fraction of the HYLIRG and ULIRG galaxies, in which emissions by young stars and a quasar within a dust cocoon are indeed mixed. Absorption and re-emission (mainly in the far IR) by the circum-nuclear dust prevent to easily distinguish the two contributions.

Once activated, the quasar will start producing enormous amounts of radiant, mechanical and particle energy, which will stop further gas accretion towards the centre and will start to expel it instead, via radiation and ram-pressure. This will evacuate the gas and dust from the nucleus and will make the quasar to shine directly in the optical bands. This is the phase corresponding to the optically bright radio-quiet quasar, dominated by the emission from the accretion disc producing the big-blue-bump between the optical and the extreme UV.

During the radio-quiet quasar phase dominated by the disc emission, the accretion disk itself transfers an amount of rotational energy to the central collapsed object. Note that the theory of thin accretion discs, as it will be discussed in Sect. 10, predicts that about half of the gravitational energy of accreting matter is emitted as quasi-thermal radiation by the disc, and roughly half is brought to the black-hole through
the inner accretion layers. It is expected that part of this may be in the form of rest-matter going to increase the black-hole mass, but part of this energy should be transferred by viscous stresses in the form of rotational energy of the black-hole itself.

Then once the fuel (accreting gas) is exhausted, or swept away by the quasar, the central black-hole will remain surrounded by a low-mass residual accretion disc and an enormous rotational energy. At this late stage of the process the bright radio-loud phase starts, with the radio-galaxy transforming in field, particle and radiant energy the rotational energy of the nuclear black-hole.