PROCEEDINGS OF SCIENCE

# Radio galaxy evolution

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In this lecture I start following a chronological thread through the discoveries on radio galaxies and especially through the speculations about their nature, their physics and their evolution. I will qualitatively describe the main progresses made during the past decades and indicate the most important (in my view!) bibliographic references if you want to dive deep into the subject. My choice to start with the early works in the sixties and the seventies is also based on the evidence that several of those seminal works are still fundamental today.

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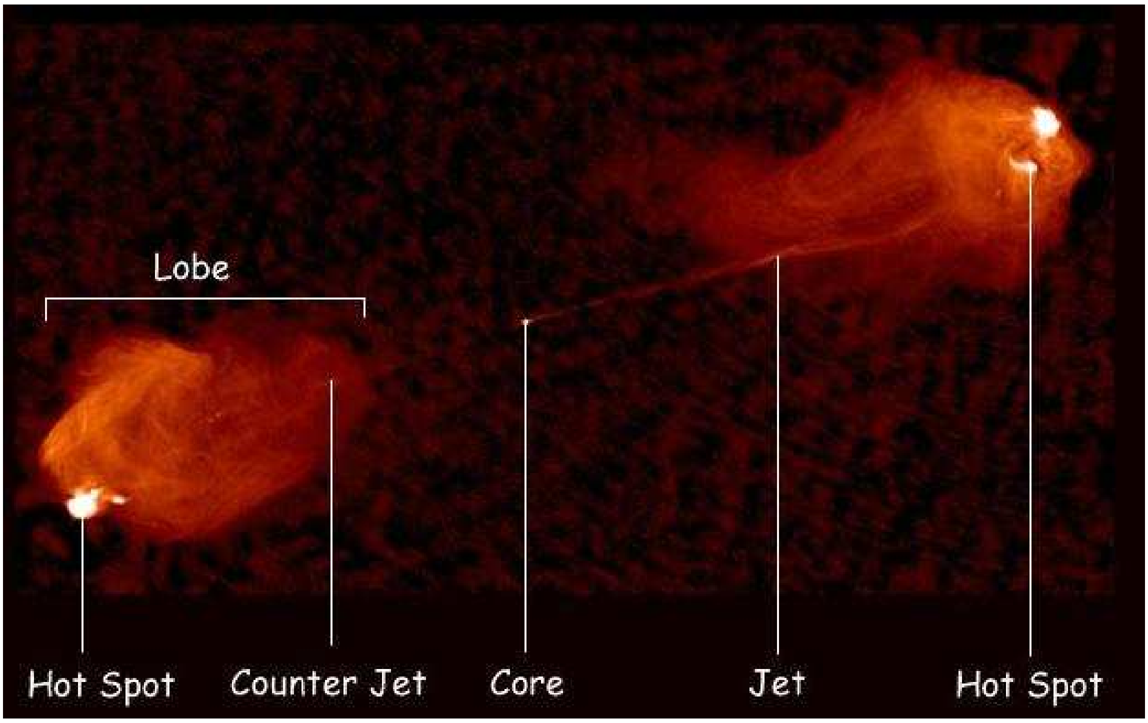


**Figure 1:** Main constituents of a radio galaxy (NRAO/AUI/NSF).

## 1. Introduction

In every galaxy there is radio emission at some level. Atomic hydrogen, molecules, active stars, pulsars, supernova remnants, diffuse cosmic rays, etc. Sometime this radio emission is relevant and deserves great attention, but not every galaxy with radio emission is a radio galaxy. We define as radio galaxy a radio source with well defined characteristics and properties. The prototypical radio galaxy is Cygnus A. In the centre of a galaxy a radio core indicates the origin of the energy feeding the radio galaxy. Two jets, not necessarily both visible, carry the energy out of the galactic envelope, terminating in two bright regions called hotspots, and forming huge structures called lobes. In low-luminosity radio galaxies jets are brighter and hot spots are missing. A small fraction of elliptical galaxies are radio galaxies.

## 2. The early days

Grote Reber has been the first “long term” radio astronomer, because Karl Jansky who first discovered radio emission coming from the Milky Way, was an engineer working for the Bell Laboratories, and after his discovery (which had more impact in the media than in the astronomical community) he stopped to work on radio astronomy because the Bell Laboratories was a private company, and no profit was foreseen by continuing the research on this radio emission of extraterrestrial origin (also, according to testimonies Karl Jansky didn’t insist too much in continuing it). Grote Reber was engineer as well. He built the telescope in the backyard of his house in Illinois at his own expenses while working full time for a radio company in Chicago. For those interested in



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the history of radio astronomy, I suggest the book “The early days of radio astronomy” edited in the 80s when many of the protagonists were still alive to tell their stories, including Grote Reber, who died in 2002.

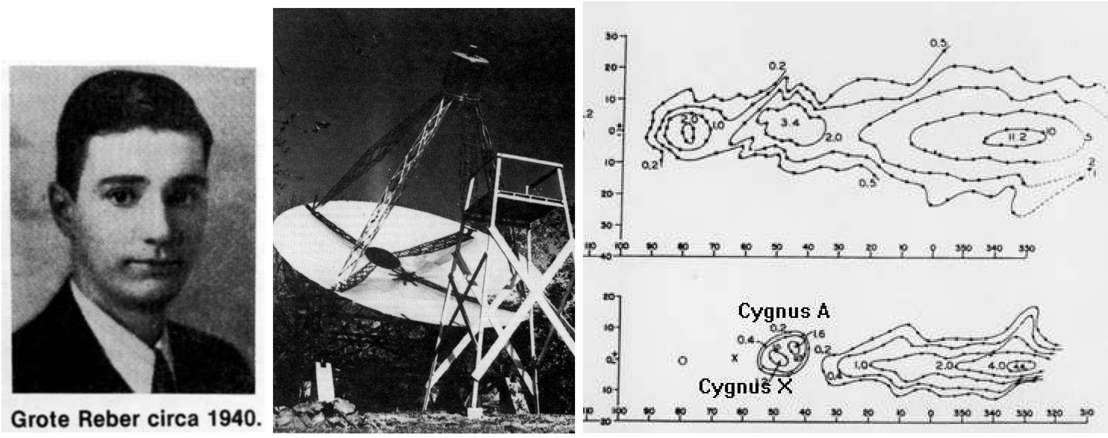


**Figure 2:** Grote Reber, his radio telescope, his first map of the radio sky.

In the following years other more powerful radio telescopes were built with better sensitivity and resolution, and many radio sources were discovered. Identification of the emitting regions with known optical objects were difficult, as the details were not at all visible even with these improved instruments.

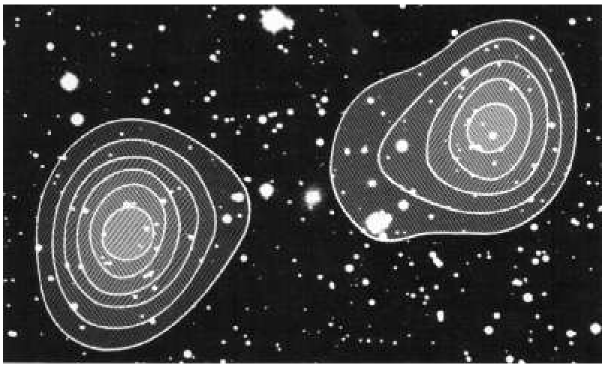

**Figure 3:** First images of radio galaxies.

At the end of the 60s it was largely accepted that most radio sources in the sky were of extragalactic origin. It the seventies many of the brightest and largest sources in the first catalogues (i.e the 3C) were identified, and a clear separation in morphology and luminosity has been discovered by Fanaroff and Riley (1974)

Extragalactic radio sources were also roughly divided in “extended” when the radio emission extends beyond the optical galaxy and “compact” when it does not.

A paper by Miley in 1980 gives a still useful description of the different morphologies observed (with WSRT, Effelsberg, Lowell, Green Bank, Cambridge, and since 1980 the VLA). You can recognize sequences and trends in edge brightness, axial ratios, symmetries, bending. Some

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examples are shown in Fig.4, with images taken by http://www.jb.man.ac.uk/atlas/, a database of images of the more prominent radio galaxies.

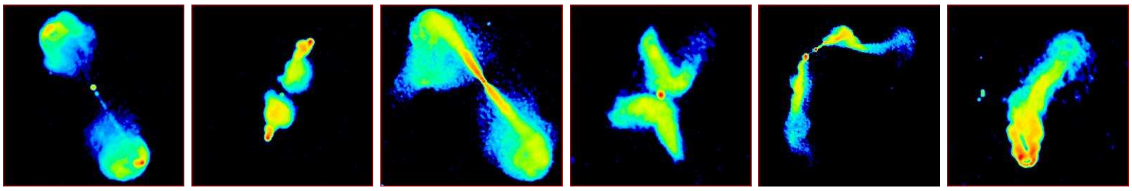

**Figure 4:** Different morphologies of radio galaxies (NRAO/AUI/NSF).

What about the compact radio sources, those smaller than a few arcseconds? At high frequencies (> 5 GHz) compact sources are the dominant population of the radio sky. Also compact sources may be divided into two main classes, the flat-spectrum radio sources and the peaked/steep-spectrum radio sources.

Flat-spectrum radio sources are not intrinsically small, but large radio sources which appear small because they are seen along the jet axis, thus the lobes are shortened by projection and the core is amplified by relativistic effects

Peaked/steep-spectrum compact radio galaxies are truly small radio sources (less than a few kpc), still imbedded in the galactic ISM, showing double-lobed structures as their larger counterparts. We will return on this subject below.

## 3. The synchrotron emission

In the forties the radiation emitted by electrons in a synchrotron, a particular type of particle accelerator, built by General Electric, was termed synchrotron emission.

Alfvén and Herlofson (1950) were the first to predict/propose that astrophysical objects could radiate by this mechanism, i.e. charged particles like electrons or positrons at relativistic energies travelling through magnetic fields emit photons strictly collimated in the direction of motion. An ensemble of electrons with a power law energy distribution would produce a radiation with a power law distribution in frequency.

Shklovskii in 1953 explained the continuum radiation of the Crab Nebula as synchrotron radiation. Burbidge in 1956 suggested synchrotron emission as the mechanism of radiation of an extragalactic radio source, trying to explain the optical emission of the jet in M87/Virgo A. Also equipartition conditions have been introduced in his paper. Today we know that M87/VirgoA is a huge nearby radio galaxy.

## 4. A model for a radio source

### 4.1 Pioneering model

Early attempts to describe the physics of a radio source took inspiration by the recent discovery of pulsars, and considered fast rotating massive objects as the source of a continuous supply of energy (Morrison 1969, Rees 1971, Longair et al. 1973).

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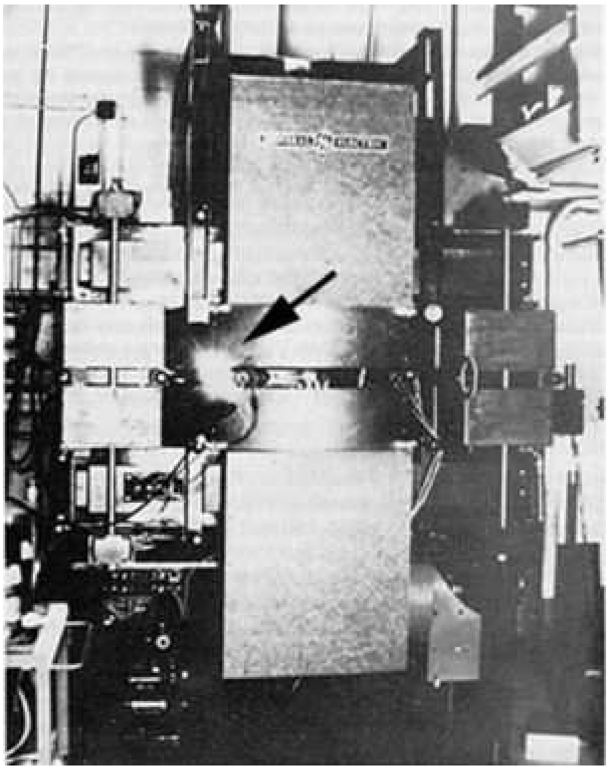

**Figure 5:** The GE synchrotron.

There was no clear idea of the nature of the rotating objects but there was already the concept that the energy to the radio source was of gravitational origin. Rees considered in his first works charged particles but also electromagnetic waves as the constituent of the jets. Already there was the idea that the energy was collimated and transported in the jet and released at the hot spot. Scheuer in 1974 presented a rather plausible model of a radio source "in which energy is carried from a nucleus to the radio components by a relativistic beam". In the Scheuer model the nature of the beam is not of much importance. It can consist of electromagnetic waves, fast particles, or be substituted by a massive object ejected by the nucleus.

To be precise he presented a few versions of a model. One with a constant jet opening angle and another one with a cylindrical jet, concluding that none was completely satisfactory, and introduced a third, only qualitative one, that would solve the problems of the first two, to match the data. He considered a model in which the energy is carried from a nucleus to the radio components by a relativistic beam. He assumed a constant density for the ambient medium, that, we will see later on, is a relevant oversimplification of his model. After the energy of the bulk motion is transformed into charged particles emitting synchrotron radiation, these particles and the energy is deposited in the lobes.

### 4.2 A twin-exhaust model for a double radio source

In 1974 Blandford and Rees presented "A twin-exhaust model for a double radio source" which is a further elaboration of the Scheuer model where the beam is composed of relativistic plasma.



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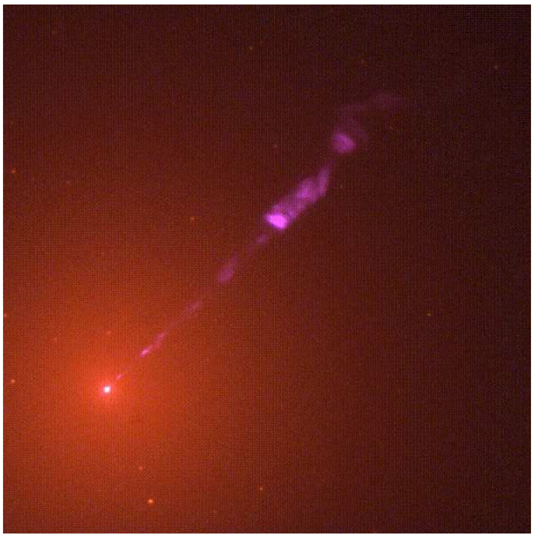

**Figure 6:** Optical jet in M87 seen by the HST.

The basic assumptions are:

- The energy is supplied by a light fluid composed of relativistic particles pervaded by electromagnetic fields which are generated in the nuclear region and collimated into two oppositely directed beams.

- Each beam is terminated, and reconverts much of its bulk energy into relativistic particle and fields at a working surface which advances outwards at a speed determined by a balance between the momentum flux in the beam and the ram pressure of the intergalactic medium.

- The energy content of extended sources can be assumed to accumulate gradually over the whole lifetime, at rates below or about $10^{45}$ erg/sec.

The mechanism of collimation and launch of the jet is still rather approximate and there are still many hypotheses about the nature of the central engine, clusters of pulsars, stars collapsing under rotational support, many black holes of stellar mass, massive objects and finally massive black holes. Even with these approximations their model has become the standard model for the description of a radio source.

## 5. Evolution of radio galaxies

Speculations about the evolution of radio sources started in the sixties. In 1962 a fundamental paper by Kardashev described the evolution of the radio spectrum with time. Other papers followed (Schmidt 1966, Kellermann 1966, Van der Laan and Perola 1969).

These studies were mainly based on the spectral properties of radio sources, and the evidence that the radiation originated from relativistic electrons radiating by synchrotron emission.

It was soon recognized that the radiative losses of the relativistic plasma reflected in the spectral shape could give an estimate of the radio source age.

These studies have shown that the radio source is a relatively short phenomenon lasting between $10^6$ to $10^8$ years. Modern applications consist in the study of different regions of a radio



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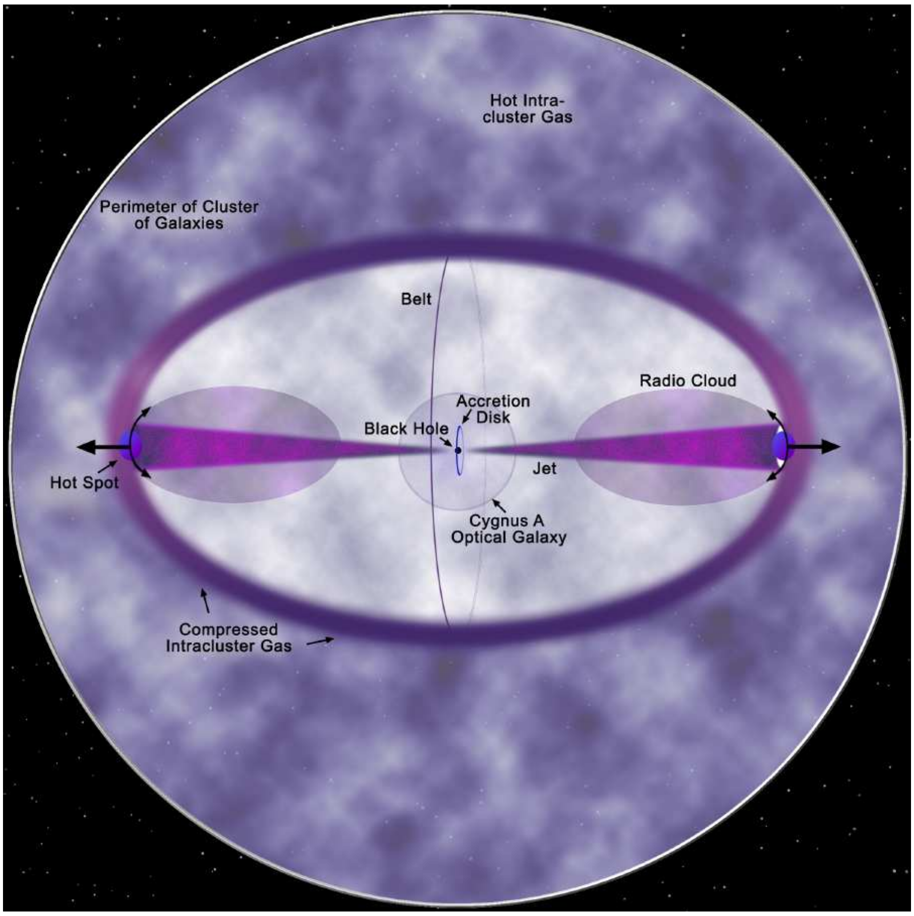


**Figure 7:** Model of a radio galaxy (NASA/CXC/SAO).

source to trace the path of the electrons, to find out where the electrons are deposited or reaccelerated.

An interesting paper by Begelman, Blandford and Rees (1984), entitled "Theory of extragalactic radio sources" presents the methods to use diagnostically the observations to infer pressures, densities, and fluid velocities within the jets.

Begelman and Cioffi (1989) suggest that the pressure of the cocoon is high enough to confine the jet. They also introduce the interesting idea that the shocked material in the jets/hotspot and cocoon may trigger star formation, which explains the alignment of the optical continuum emission with the radio axis.

High-luminosity radio galaxies look similar at any size. Their axial ratio does not correlate with size. These general arguments and numerical calculations are used by Falle (1991) to show that the flow caused by a supersonic jet is self-similar under certain conditions.

In 1963 the Russian astronomer Shklovskii introduced the P-D diagram for RS, plotting the (projected) size versus power. The P-D diagram is the radio equivalent of the H-R diagram for stars, except that for stars the evolutionary tracks on this diagram are known in great detail, while for the radio galaxies is still unknown or controversial.

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FRI radio sources, i.e. the weaker radio sources where the jet is not powerful enough to become supersonic, are difficult to measure in size, because they do not have bright edges. Therefore the following consideration and the models will apply to the FRII radio sources only.

Baldwin in the paper "Evolutionary tracks of extended radio sources" (1982) using Scheuer dynamical model and a decreasing density profile of the IGM traces evolutionary tracks on the P-D diagram.

Evolution in power and luminosity is governed by adiabatic losses as lobes expand, synchrotron radiation losses in the lobe magnetic fields, and inverse Compton (IC) losses off the cosmic microwave background photons.

Generally the models assume that the radio source grows in an environment with gas density described by:

$$\rho(r) = \rho_0(\frac{r}{a_0})^{-\beta}$$

Kaiser and Alexander (1997) propose a model for extragalactic radio sources with a pressure-confined jet expanding in a self-similar way into a spherically symmetric atmosphere with a density profile falling less steeply than $1/d^2$. There should be stable laminar jets for jet powers above the FRI/FRII divide.

Kaiser, Dennett-Thorpe and Alexander (1997) plot evolutionary tracks of FRII sources through the P-D diagram. Hot spot pressure drives the source expansion along the jet axis and the cocoon pressure drives the expansion perpendicular to the jet axis. Considering energy-losses for the relativistic electrons, evolutionary tracks through the power linear size diagram are calculated. The authors conclude that cocoons can have self similar growth. The evolutionary tracks are found to be insensitive to the assumed form of the magnetic field evolution. They also claim evidence against protons as a major constituent of the jet material.

Blundell, Rawlings and Willott (1999) refine the model of the source growth considering the shock front of the jet (hot spot) much smaller than the observed bright "head" of the radio source. The rate at which the source grows into its environment is governed by the pressure of the head.

Manolakou and Kirk (2002) consider the same picture as in Blundell et al. (1999), but assume that adiabatic losses between the hot spot and the lobe are compensated by subsequent weaker shocks through which the plasma passes after the termination shock at the primary hot spot and before emerging into the lobe.

Barai and Wiita (2006) generate simulated suveys which are allowed to evolve according to the previous models. No existing model gives excellent fits to all the data simultaneously. The model of Kaiser et al. is the best in fitting the observational data. In a second paper (Barai and Wiita, 2007) the authors allow the growth of the hot-spot size. This improves the match between simulated and real data, which however is still not entirely satisfactory. They also address cosmological aspects as radio galaxies may have substantial impacts on the formation, distribution and evolution of galaxies and large scale structure in the Universe. Radio galaxies trigger star formation in the IGM. The expanding radio lobes could have infused magnetic fields of significant strengths ($10^-8$G) in the IGM. The radio lobes may also be responsible of spreading metals in the IGM. The authors stress the importance to address the problem of which fraction of the "relevant" Universe has been filled by the radio lobes.



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## 6. Smaller sources

The evolutionary models discussed so far where about the growth and evolution of an already established radio galaxy in the intergalactic medium, during the time it is supplied with fresh electrons from the nucleus. In the following I will consider the early phases of a radio source life. To study and understand the origin of radio galaxies and the early stages of their evolution, it is important to find the youngest between them. To this purpose, we need to search for the most compact sources with the same morphology as the largest ones, i.e. with a two-sided structure characterized by lobes dominating the radio emission with two bright hot-spots at the edges, provided the angular resolution is sufficient to disentangle their emission within the lobes. In general, the radio core accounts for a tiny fraction of the total flux density on all scales, and, due to limitations of dynamic range, sometimes is undetected in the smallest objects.

### 6.1 Where to find young radio galaxies

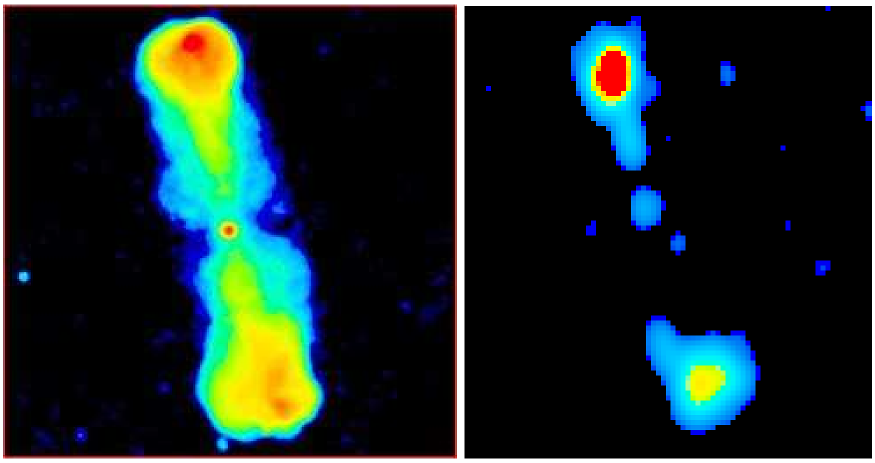

**Figure 8:** 3C35 (left) and J1335+5844 (right) have the same morphology on very different scales; J1335+5844 has an angular size of 14 milliarcseconds while 3C35 is more than 50000 times bigger.

To find young radio sources we may look for compact sources with the same morphology as the large ones (assuming they maintain their basic structure during their lifetime). These sources are known as Compact Symmetric Objects (CSO, < 1kpc) and Medium Size Objects (MSO, 1-20 kpc). They generally have a convex or steep radio spectrum (flux density versus frequency).

### 6.2 Young or frustrated?

Indeed youth is not the only explanation for CSOs and MSOs. In the past years, two main scenarios have been proposed to explain the compactness of these radio sources.

The *youth* scenario (Phillips & Mutel 1982, Fanti et al. 1995, O'Dea & Baum 1997; Alexander 2000; Snellen et al. 2000, 2003), suggests that CSOs are small because they are young, and that in the course of their life they will expand outwards in a self-similar way.

In the *frustration* scenario (e.g., van Breugel et al. 1984; De Young 1993; Carvalho 1994, 1998), the radio emitting plasma is confined (for the lifetime of the radio emission) to a region



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within the host galaxy by an external medium that is dense enough to prevent the expansion of the radio source.

Both the "youth" and the "frustration" scenarios are motivated by the morphological similarity between the small CSOs and the extended radio galaxies, while the frustration scenario, if valid for most CSOs, can also explain the evidence that there are too many small sources if they spend only 1/100 or 1/1000 of their lives in the CSO phase.

Variations or complications of these scenarios may include recurrency, which means radio sources die and start again several times, and/or the possibility that a fraction of them are short lived, i.e. can die young because of episodic fuelling, maybe triggered by a recent merger event.

To see whether there is enough gas to confine and stop the expansion of the radio emitting plasmoids, we can try to probe the central regions of the hosting galaxies by means of radio observations at 21 cm to look for HI (Pihlström et al. 2003, Vermeulen et al. 2003, Orienti et al. 2006), infrared observations to find cold gas (Fanti et al. 2001), X-ray observations to find X-ray emitting hot gas or absorbing cold gas (Guainazzi et al. 2006, Vink et al. 2006) or we can study the depolarization of the radio emission to look for ionized gas (Fanti et al. 2004). Even if substantial information can be derived from these observations, there is no conclusive evidence of the presence of enough gas to stop the expansion. On the other hand, on the very small scale ($<$1 kpc), it seems that the gas, when present in great quantity, is confined to a disk and/or torus in a plane perpendicular to the radio axis, and therefore not directly interacting with the expanding jets.

A strong support for the youth scenario comes from the determination of the age by means of the direct observation of the radio source expansion. In CSOs with well-defined hot-spots, observed over time-baselines spanning several years, relative separation speeds of $0.1 - 0.3c$ have been found, implying ages of the order of a few thousand years (Polatidis and Conway 2003).

The evidence for youth is strengthened by the determination of the age derived by the steepening of the radio spectrum caused by the radiative losses. In the lobes of CSOs, where the old electrons are deposited during the lifetime of radio sources, ages of thousands of years have been calculated (Murgia 2003), well in agreement with the dynamical ages determined by expansion velocities.

### 6.3 Modelling the radio source growth

The first analytical model for the first stage of a radio source growth was presented by Begelmann (1996). In his model, the expansion velocity weakly depends on the source size, while the luminosity decreases with the square root of the size, giving rise to FR Is or FR IIs depending on the initial luminosity. Begelman does not compare the predictions of his model with the observations.

To have a quantitative and rigorous approach, we should compare models of a radio source evolution with the distributions of linear sizes of the samples of young radio sources.

Several samples of candidate young radio sources sources have been selected in the past years (Spencer et al. 1989, Fanti et al. 1990, Stanghellini et al. 1998, Snellen et al. 1998, 2002, 2004, Marecki et al. 1999, Dallacasa et al. 2000, Fanti et al. 2001, Kunert et al. 2002, Bolton et al. 2004, Edwards and Tingay 2004, etc.). They cover different regions in the turnover frequency – brightness domain, thus they are not simply duplications of each other.

Three evolutionary models have been developed in more recent years (Snellen et al. 2000; Alexander 2000; Tinti & De Zotti 2006), which make use of several of the samples mentioned



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above. They have significant different predictions about self–similar expansion, radio-power evolution, existence of short-lived objects, cosmological evolution of the luminosity function, etc. These differences strongly depend on the assumptions made to combine the different samples, and on the corrections applied to account for the various selection criteria.

It is evident that the observational data are not sufficient to constrain the models, as there are too many different samples, each one covering only a fraction of the peak-frequency – brightness domain. Therefore, a single complete sample of a few hundreds objects spanning more than two decades in turnover frequency, and with a low flux-density limit would be extremely useful to better constrain the models. This can be obtained by means of selecting a completely new sample, or complementing/combining some of the existing complete samples with new observations to avoid the problems mentioned above.

Another crucial piece of information to constrain these evolutionary models is the measurement of the expansion velocity since it is related to the radio power and to the local ambient density. Reliable proper-motion measurements based on hot-spot velocity separation are available only for about a dozen sources, including upper limits, while for an additional dozen of sources with only sparse observations, proper motions are suspected (Polatidis & Conway 2003, Gugliucci et al. 2005). Furthermore, the expansion speed of $0.1 - 0.3c$ have been measured for the bright and luminous objects. It is possible that weaker radio sources have a slower growth or are even confined. It is, therefore, essential to increase the number of reliably measured expansion velocities in order to make a statistically significant analysis. This can be achieved thanks to multi-epoch VLBI monitoring of a large number of GPS and CSS with the currently available VLBI networks. The detection of proper motions in GPS and CSS requires high-resolution observations spanning several years, and it is therefore a time-consuming effort. However, it is a very powerful tool to understand the dynamical evolution of newly-born radio sources and set constraints on the current models. By increasing the number of sources with measured expansion (or with stringent limits), we can correlate it to the size, power and morphology of these sources and test the existence and fraction of frustrated objects.

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