Low Frequency Spectral Studies of Extragalactic Radio Sources

PhD Thesis

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Outline of the thesis

Modern radio interferometers can produce higher resolution images than any other type of telescope. At frequencies greater than 1 GHz, arcsecond, and even sub-arcsecond, resolution images are routinely obtained by arrays with baselines longer than tens of kilometers. At lower frequencies the wavefront is corrupted as it propagates through the Earth’s ionosphere and its phase coherence is lost on baselines longer than about 5 km. For this reason, the low frequencies arrays that have been built have very short maximum baselines and thus poor angular resolution. The limited angular resolution of these arrays also results in severe degradation of their imaging sensitivity due to the confusion noise of the large number of background sources that populate the low frequency sky.

The situation changed at the end of the 90’s, when the National Radio Astronomy Observatory and the Naval Research Lab implemented the 74 MHz receiver system at the Very Large Array (VLA). With a maximum baseline of 35 km, the VLA provides an angular resolution of 22 arcseconds at this frequency. Self-calibration was found to be effective in removing ionospheric effects, at least to first order. For the first time it was opened the possibility to observe the sky at very low frequencies with unprecedented resolution and sensitivity.

However, there are several major difficulties in the reduction of low frequency data. Besides the effects of the ionosphere, the most important are terrestrial radio frequency interferences, the non co-planarity of the field of view, and the large number of non-target sources in the field of view. New observing strategies and calibration procedures have been proposed to overcome these problems. These techniques are still under development and constant refinement also thanks to the continuously growing computational power. Despite these technical difficulties there are strong scientific drivers justifying sensitive low frequency observations. In fact, the next generation of radio interferometers (LOFAR, SKA, LWA) will largely operate in this region of the electromagnetic spectrum.

The original motivation of this thesis work was to acquire experience in the planning, realization, and data reduction of low frequency observations with the VLA. We observed at 74 and 327 MHz with the VLA in different configurations two radio halos and two giant radio galaxies for which we already have data at higher frequencies. Due to their steep spectra and large angular sizes, these synchrotron radio sources are among the best targets for low frequency observations. By combining
the images obtained at low frequencies with those available at higher frequencies we studied the variations of the synchrotron spectrum point-to-point across these sources. We observed the radio halos in the clusters of galaxies Abell 2219 and Abell 2744. Radio halos are wide diffuse radio emissions detected at the center of merging clusters of galaxies. The origin of the relativistic electrons and magnetic fields in these low surface brightness sources is still matter of debate. Spectral information can give useful constraints to the models proposed to explain the nature of these radio sources. Giant radio sources are supposed to be old radio galaxies evolved in a low density ambient. Spectral studies can be used to estimate the radiative ages of the relativistic electrons. We derived the detailed shape of the synchrotron spectrum along the lobes of the giant radio sources 3C 35 and 3C 223 obtaining the ages of these sources and their expansion speeds.

This thesis is organized as follows:

A brief description of the basic passages which lead from the beginning of observations to the final interferometric images are described in Chapter 1.

In Chapter 2 we describe the main difficulties which intervene in low frequency observations and the solutions currently adopted to overcome these problems.

In Chapter 3 observations at 327 MHz of the radio halos in A2744 and A2219 are presented. We derived the spectral index images and radial profiles between 327 MHz and 1.4 GHz. The results are discussed in the framework of the current models proposed to explain the origin of the synchrotron electrons in these sources.

In Chapter 4 we presented observations at 74 MHz of the giant radio sources: 3C35 and 3C223. We performed a spectral analysis combining 74, 327, 608, 1400 MHz images of matched resolution and we derived the spectral aging of the electrons along the main axis of these sources.

Chapter 5 gives a brief summary of the work done and of results obtained.

The main results of the radio halo low frequency observations presented in this thesis are the subject of the paper: Low-Frequency study of two clusters of galaxies: A2744 and A2219 accepted by Astronomy & Astrophysics by E. Orrù, M. Murgia, L. Feretti, F. Govoni, G. Brunetti, G. Giovannini, M. Girardi and G. Setti

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Radio Interferometry

Abstract
Astronomical objects emit electromagnetic radiation from the radio waves to the \( \gamma \)-rays, the observation of this emission from the Earth is allowed in a limited range of wavelengths, since the absorption or reflection of the atmosphere. The radio and the optical bands are the only two transparent windows to the electromagnetic radiation from the Earth. The first generation of radio telescopes able to detect radio waves was mainly based on single dish antennas. In the view to distinguish fine details in the sky, long wavelength observations would need huge diameter antennas, this is limited by technical and financial reasons. A great improvement in terms of angular resolution has been introduced with the advent of interferometers. One interferometer is constituted by a number of small single dishes, where the signals from each of these antennas is combined in order to simulate a single radiotelescope with dimensions comparable with the largest distance between a pair of antennas. The answer of the radio interferometer is the visibility, a complex function, whose amplitude is related to the observed intensity and the phase gives the information on the position and the structure of the observed source. The extraction of the image of the sky is obtained following a number of steps: calibration, Inverse Fourier transform, deconvolution of instrumental effects and restore. The aim of this chapter is to describe, after a brief historical overview, the main passages which lead from the beginning of the observation to the production of the final interferometric image.
1.1 Introduction

The study of the visible light of the Universe started many centuries ago, at the beginning by simply looking at the objects, later by using telescopes [Michelson & Pease 1921].

The first radio astronomical observations were made by Karl Jansky in 1932 who, serendipity detected cosmic radio signal from the center of the Milky Way Galaxy. Few years later, Grote Reber built the first radio telescope and found that the radio radiation comes from all along the plane of the Milky Way and from the Sun. The first generation of radio telescopes developed following the feature of optical telescopes, therefore was mainly based on single dish antennas. These are composed by two principal elements: the antenna which collects the electromagnetic radiation and the feed in which the signal is revealed. The angular resolution of the single radiotelescope is \( \theta \propto \frac{3437.7467550 \lambda}{D} \), where \( \lambda \) is the observing wavelength and \( D \) is the diameter of the antenna. An antenna of 100 m of diameter, as the Effelsberg single dish, observing at 21 cm the angular resolution is about 9' (Fig. 1.1). At radio wavelength the extreme imbalance between the excellent sensitivity and the poor angular resolution reached by single antennas led to the development of the radio interferometric technique.

One of the most notable developments came in 1946 with the introduction of radio interferometry by Martin Ryle 1946 (see Ryle & Vonberg 1946) who constructed a radio interferometer analogue of the optic interferometer made by Michelson. In the 1974, he obtained the nobel prize for this and later for the aperture synthesis develop (e.g. Ryle & Hewish 1960).

For the next three decades astronomical radio interferometry research has been motivated in order to reach more and more high resolution power, leading to the development of large instruments as e.g. the 5 km Ryle Telescope in Cambridge where Martin Ryle and colleagues developed the technique of Earth Rotation Aperture Synthesis, the Westerbork Synthesis Telescope (WRST) with 10 antennas of 25 m (1956), Very Large Array (VLA) with 27 antennas of 25 m (1980), the Australia Telescope Compact Array (ATCA) with 6 antennas of 22 m (1988) and the Giant Meter Radio Telescope (GMRT) with 30 antennas of 45m (1995). Moreover it has been developed the technique of Very Long Baseline Interferometry (VLBI) which permits to contemporary record data in many observatories located in different countries and subsequently correlate them. Since the baselines reach thousands of meters, this permits to obtain very high angular resolution of the order of milli-arcseconds.

Next generation of radio telescope is driven to study the boundary frequencies of radio window, for instance: LOw Frequency ARray (LOFAR) and Long Wavelength Arrays (LWA) for frequency lower than 1 GHz and Atacama Large Millimeter Array (ALMA) for millimeter wavelengths.
1.2 Elements of Radio Interferometry:

Interferometers are constituted by a number of small elements, like pieces of a giant single dish antenna; the signals from each antenna are combined in order to simulate a single radiotelescope with dimensions comparable with the largest distance between a pair of antennas. The effect of the electromagnetic signal on the interferometer is the analogue to that produced on a diffraction grating with finite apertures. As well for the diffraction grating also in radio astronomy the assumptions of the Fraunhofer diffraction must be satisfied. In particular, the incoming wavefronts must be considered to be plane, therefore the location of the target source must be in the far field from the interferometer: $R \gg a^2/\lambda$. For observations at 20 cm with the VLA where the largest distance
between two antennas, \( a \), is about 36 km, the distance of the source must be \( R \gg 4 \) UA, which is about the distance from the Earth to Jupiter; with the typical distance of antennas of about 10000 km used in the intercontinental interferometry (VLBI), \( R \) must be \( \gg 3300 \) UA, which is more than the distance of Proxima Centauri.

As for the diffraction grating, the diffraction image is function of the relative distance between the apertures, also in the interferometer the output is function of the distance between the antennas. Similarly, because of the angular resolution is inversely related to the distance between the apertures, in the interferometer the progressively increase of the distance between antennas, implies an improvement on the angular resolution of the target source. The largest and the smallest angular structures that could be achieved by the interferometer depend on the smallest and the largest baselines, respectively.

In the simplest interferometer (Fig. 1.2) two antennas separated by the distance \( b \), \textit{baseline}, point toward a distant source in the direction indicated by the unit vector \( \mathbf{s} \). Since the physical path caused by the relative orientation of the interferometer baseline and the direction of the wave propagation (\( \mathbf{s} \)), the wavefront does not reach the two antennas at the same time. The time delay, called \textit{geometrical delay}, is \( \tau_g = \mathbf{b} \cdot \mathbf{s} / c \), where \( c \) is the speed of light.
1.2 Elements of Radio Interferometry:

Assuming that, antennas have the same gain, the electromagnetic fields of frequency \( \nu \) induced at the output of the two antennas are:

\[
E_1(t) = E \sin(2\pi \nu t) \quad (1.1)
\]

and

\[
E_2(t) = E \sin[2\pi \nu (t + \tau_g)] \quad (1.2)
\]

The signal of each pair of elements is correlated, i.e. multiplied and integrated over the time \( T \), we have:

\[
R(\tau) \propto \frac{1}{T} \int_0^T E^2 \sin(2\pi \nu t) \sin[2\pi \nu (t + \tau_g)] \, dt. \quad (1.3)
\]

In theory, the operation of correlation mean an infinite time of integration, but in practice a good assumption for the integration time is to take \( \tau_{\text{int}} \gg \nu^{-1} \); that is to say that a large number of oscillations of the signal must occur in the time \( \tau_{\text{int}} \):

\[
R(\tau) \propto \frac{1}{\tau_{\text{int}}} E^2 \int_{-\tau_{\text{int}}/2}^{\tau_{\text{int}}/2} \sin(2\pi \nu t) \sin[2\pi \nu (t + \tau_g)] \, dt, \quad (1.4)
\]

the result is:

\[
R(\tau) \propto E^2 \cos(2\pi \nu \tau_g). \quad (1.5)
\]

In practice, after the integration in time, which value in a typical observation is about 10 seconds, in the answer of the interferometer the term of oscillation of the incident electromagnetic waves is lost and only the term introduced by of the geometrical delay is kept. The term \( |E|^2 \) is the power density, the term \( 2\pi \nu \tau_g \) is the phase difference between the two electric fields induced the geometrical delay. If the baseline orientation and the wave propagation direction remains invariable, \( \tau_g \) remains constant. However, due to the Earth rotation, the angle \( \theta \) (Fig. 1.2) between the wave propagation direction and the axis perpendicular to the baseline changes slowly therefore also \( \tau_g \) vary, as a consequence we will measure interference fringes as a function of time.

The crucial point in interferometric observations stays in the fact that phase term is preserved, this implies that also the position of the observed source is preserved. This is possible because the coherence of the radiation is preserved. Actually, the wavefront is not precisely plane since the distortions produced in the diffusion of the wavefront in the atmosphere. In practice, in radio astronomy, the phase errors generated in by these distortions are negligible with respect to the geometrical delay, therefore the wavefront can be assumed to be plane and the source position can be found. Since the answer of the interferometer gives the measure of the coherence of the electromagnetic field it is often called mutual coherence function.
According to the antennas’ theory, the effective aperture of the antenna is: $A_e = \eta A_g$, where $A_g$ is the geometric aperture and $\eta$ is the aperture efficiency.

The flux (measured in Jy\footnote{The flux unit or jansky (symbol Jy) is a non-SI unit of electromagnetic flux used in radio astronomy, it bears his name; $1 \text{Jy} = 10^{-26} W m^{-2} Hz^{-1}$ (SI), $1 \text{Jy} = 10^{-23} \text{ergs}^{-1} cm^{-2} Hz^{-1}$ (cgs).}) is the quantity which describes the power collected over the solid angle $\Omega$: $S(\nu) = I(\nu)\Omega$, where $I(\nu)$ is the brightness or intensity.

The antenna collects a total power of $E^2 = A_e I(\nu)\Omega$, therefore the answer of the interferometer is function of the brightness of the sky.

In the analysis of a simple interferometer it is convenient to specify the angles of the antenna beam and other variables with respect to reference position on the sky, which is usually the center of the observed source or field, phase reference position, $\theta$ in Figure 1.3.

In figure 1.3, we illustrated the polar plot of the effective area of the power pattern of the antenna $A(\theta)$ and in blue the one-dimensional intensity profile of a source, in which $\theta'$ is the position with reference to the phase center.

Observations are modified by the presence of the instrument used to do the measure, these are the result of a weighted average of values close to the real values. According
to this the response of a single antenna is given by the cross correlation between the
pattern and the intensity distribution of the source (in this reference system).

\[
\int_{\text{source}} A(\theta' - \theta) I(\theta') d\theta'.
\]  (1.6)

If we define \( A(\theta) = A(-\theta) \), this can be expressed in terms of a convolution between
the antenna pattern and the intensity distribution of the source:

\[
\int_{\text{source}} A(\theta - \theta') I(\theta') d\theta'.
\]  (1.7)

For simplicity we consider an interferometer with tracking antennas. Moreover, if we
define \( u = \frac{b}{\lambda} \), this represents the spatial frequency and \( l \) is the positions in the sky
with respect to \( u \).

The response of the interferer is determined by the power pattern of the antennas
and the fringe pattern introduced by the geometrical delay (Eq. 1.5). Therefore it
can be expressed in terms of the convolution between the fringe pattern (the mirror
image) and the modified intensity:

\[
R(l) = \int_{\text{source}} \cos[(2\pi u(l - l'))] I_l(l') A(l') dl'.
\]  (1.8)

Omitting the antenna pattern dependence the response of an interferometer can be
written as:

\[
R(l) \propto \cos(2\pi ul) * I_l(l)
\]  (1.9)

According to the convolution theorem the Fourier transform of the convolution is
the product of their Fourier transform; therefore for the equation 1.9 the response
\( R(l) \) in the sky coordinates is the Fourier transform of \( r(u) \) in the spatial frequency
coordinates and vice-versa.

The Fourier transform of the intensity \( I_l(l) \) is the visibility function \( V(u) \).

In practice, the amplitude term in the visibility depends on the intensity of the source,
because of the complex nature of the visibility it is possible to measure the brightness
of the sky by its Fourier inversion, this is the content of the “Fundamental theorem
of the interferometry”.

The visibility is a complex quantity which represents the spatial frequency spectra,
with units of \( \text{W m}^{-2} \text{Hz}^{-1} \).

The simple interferometer with two antennas is one-dimensional therefore at any
instant of time it will produce a response in one direction only. In order to sample
different spatial frequencies, we have to combine many elements and use the rotation
of the Earth, this technique is called aperture synthesis.
In a single dish telescope radiation is reflected from different elements of the surface to the focal point where the signal is detected. In aperture synthesis the individual surface elements can be conceived as the small antennas. If we have only two segments we could simulate the effect of a larger dish by moving one segment around the other and adding together all the combinations of signals. Moreover, instead of having a direct path to a common focal point the signals are carried by cables to a central location, where they are combined in pairs. Instead of moving each dish we can take advantage from the rotation of the Earth that changes the orientation of the baseline with respect to the object we are observing, therefore at any instant each pair of antennas observes a celestial object at only one position angle. According to the Fig. 1.2 at any instant each pair of antennas points in a “sharp” \( \theta \) in the sky. The signals from each dish are combined in the correlator. As the Earth rotates, causing each pair of reflectors to trace an annulus, or ring, under the source, changing the aspect of the source as it is seen from the array. Therefore in the course of the day the object is observed at all position angles and the annulus is completely filled in. If we sampled the signal with antennas in every possible position we would produce the image that would be obtained with a completely filled-in dish.

### 1.3 Visibility and \( uv \)-plane

In this section we will treat the visibility in a coordinate system perpendicular to the Earth rotation, called \( uv \)-plane.

In the following, as showed in Fig. 1.4, we will consider a coordinate system in which the baseline components are \((u, v, w)\), where the \( u \)-axis is in East direction and \( w \) points in the direction of interest. As showed for one-dimensional case in figure 1.3, here the positions in the sky are indicated with \((l, m, n)\), the direction cosines measured with respect to the \((u, v, w)\).

We use a coordinate system in which the image center is chosen to be at the position of phase zero. If all phases are adjusted to produce a zero delay at the image center, the answer of the interferometer will be referred to this position, \( s_0 \), that become the center of the synthesized image (Fig. 1.4) and to the baseline expressed in wavelengths units \( \frac{\lambda b_\lambda}{c} = D_\lambda \). Since the fringe term is given by \( \nu \tau_g = D_\lambda \cdot s \), with respect to the phase center it will be: \( D_\lambda \cdot (s_0 + \sigma) \), where \( \sigma \) is the distance between the phase center and \( s \). The visibility function will be:

\[
V = \int A(\sigma) I(\sigma) \cos(2\pi D_\lambda \cdot \sigma) \, d\Omega, \tag{1.10}
\]

where \( d\Omega = \sin \theta \, d\theta \, d\phi \) is expressed in polar coordinates.

In this new system the phase term will be:

\[
D_\lambda \cdot s = ul + vm + wn,
\]
1.3 Visibility and uv-plane

Figure 1.4: Right-handed coordinate systems used to express the interferometer baselines, \((u, v, w)\), and the source brightness distribution, \((l, m, n)\) (Taylor et al. 1999).

\[ D_\lambda \cdot s_0 = w \]
and the \(d\Omega = \frac{dl\, dm}{n} = \frac{dl\, dm}{\sqrt{1-l^2-m^2}}. \)
Therefore \(D_\lambda \cdot \sigma = D_\lambda \cdot s - D_\lambda \cdot s_0.\)

If we consider the assumption of a tracking array, the antenna patterns remain centered on the same point in the target source; therefore the array measurements will be the product of the source intensity with the antenna pattern.
The expression of the visibility (Eq. 1.10) will be:

\[
V(u, v, w) = \int \int A(l, m)I(l, m) e^{-2\pi i(u l + v m + w(\sqrt{1-l^2-m^2}-1))} \frac{dl\, dm}{\sqrt{1-l^2-m^2}}. \tag{1.11}
\]

where \(A(l, m)\) is the factor which takes into account of the different sensitivity of the antennas in different directions (effective area), while \(I(l, m)\) is the observed intensity.

In the case of small field imaging, the dependence of the visibility upon \(w\) can be
omitted because:
\[
(\sqrt{1 - l^2 - m^2})w \approx -\frac{1}{2}(l^2 + m^2)w \approx 0
\]
Then the equation 1.11 becomes:
\[
V(u, v) = \int \int A(l, m)I(l, m) e^{-2\pi i(ul + vm)} \, dl \, dm.
\tag{1.12}
\]
The brightness distribution of the source is obtained from the visibility Fourier inversion of the equation 1.12:
\[
A(l, m)I(l, m) = \int \int V(u, v) e^{2\pi i(ul + vm)} \, du \, dv.
\tag{1.13}
\]

The interferometer observes a point on the celestial sphere, the rotation of the Earth causes the \(u\) and \(v\) components of the baseline to trace out an elliptical locus. The ellipse is the projection onto the \((u, v)\) plane to the circular locus traced out by the tip of the baseline vector. Moreover, since the brightness is a real function, i.e. in each point it is defined by one value, its Fourier transform is hermitian, then \(V(-u, -v) = V^*(u, v)\). Thus the interferometer also determines along a second ellipse, the reflection through the origin of the first (Fig. 1.5 Left).

An interferometer with \(n\) antennas will have \(n(n-1)/2\) baselines, the two-dimensional Fourier transform would give a map of the portion of the sky under observation (Fig. 1.5 Right). In practice the interferometer works as a filter towards the spatial frequencies proper of the radio sources in the range of spatial frequencies fixed by the smallest and the largest baseline. It will be able to detect structures in the range between \(\frac{1}{u_{\text{max}}}\) and \(\frac{1}{u_{\text{min}}}\). Unlike the filled aperture, in the interferometer the baseline zero as the fringe visibility \(V(u_0, v_0)\) do not exist.

### 1.4 Synthesized beam

For an interferometer with \(n\) antennas, the \(wv\)-plane is sampled in \(n(n-1)/2\) baselines, thus it is not fully covered (Fig. 1.5 Right).

The \(wv\)-plane coverage is described by a sampling function \(g(u, v)\) which is one for all data points and zero for the rest.

Considering the sampling function \(g(u, v)\), for a source of intensity \(I(l, m)\) with the antenna pattern \(A(l, m)\) the measured visibility \(V(u, v)\) will be:
\[
[V(u, v) \ast \bar{A}(u, v)]g(u, v),
\tag{1.14}
\]
where the asterisk indicate the convolution and the bar the Fourier transform. The image, which will results in this case; by the Fourier transform of the equation 1.14.
1.4 Synthesized beam

will contains only those spatial frequencies for which the visibility has been measured; it is called **dirty image** and could be described as follows:

\[
I^D(l, m) = [I(l, m)A(l, m)] * \hat{g}(l, m).
\]

(1.15)

The function which represents the “filter” according to which the interferometer sees the intensity of the sky is the point spread function or **synthesized beam**. It is defined as the response of the interferometer to a point source, it is given by:

\[
B(l, m) = \int \int g(u, v)e^{2\pi i(ul+vm)} du dv,
\]

(1.16)

then \(I^D(l, m) = I_\nu * B\) (Fig. 1.6).

Therefore the images are affected by the shape of the synthesized beam of the interferometer. In designing arrays, it is very important to cover the \(uv\)-plane as widely and as uniformly as possible.

In order to obtain the image of the brightness, dirty images must to be deconvolved for the synthesized beam. The **CLEAN** is one of the most common procedure between the operations of deconvolution, see e.g. Högbom (1974), Clark (1980) or Schwab (1984).
In a typical VLA observation of one hour with an integration time of 10 seconds 10000 visibilities are registered, the use of the Fast Fourier Transform (FFT) is needed. In this case, it is required to interpolate the data onto a regular grid. This operation is called resampling, one of its effects is the aliasing, that is the replication of the image outside the synthesized field, this can be reduced using a thicker grid. Since the images produced by the FFT contains features that are artifacts of the beam shape, non-linear operations of deconvolution are usually applied to improve interferometric images.

1.5 Amplitude and Phase calibration

In the previous sections we describe how a two-element interferometer measures the spatial coherence function of the radiation field. An array of n-antennas samples the visibility function at many different location, thus after the amplification, correlation and average of the observed visibility differs from the spatial coherence function. The aim of the calibration is to find suitable parameters in order to estimate the true visibility. It can be expressed as follows:

\[ V_{ij}^{\text{obs}}(t) = G_{ij}(t) V_{ij}^{\text{true}}(t) \]  \hspace{1cm} (1.17)

where \( G_{ij} \) is the gain which is a complex function.

There are two ways of approach in the measure of the gain parameters: baseline-based or antenna-based. In the first way the estimated gains are the observed complex visibilities of the calibrator, divided by its flux density, S; they are described by:

\[ G_{ij}(t) = \frac{V_{ij}^{\text{obs}}}{S} \]  \hspace{1cm} (1.18)
1.5 Amplitude and Phase calibration

Since most of data corruptions occurs before the correlation of the signals, the antenna-based method is preferred. We can write:

\[ G_{ij}(t) = g_i(t)g_j^*(t)g_{ij}(t) \]  

(1.19)

where \( g_i(t) \) is the antenna-based complex gain for \( i \) antenna and \( g_{ij}(t) \) is the residual baseline-based complex gain, called “closure error” it is \( = 1 \) if the baseline gain is perfectly factored into a product of antenna gains. The equation (1.19) can be separated in amplitude and phase gain terms. The calibration equations become:

\[ A_{ij}^{\text{Obs}} = a_ia_ja_{ij}S \]  

(1.20)

and

\[ \phi_{ij} = \phi_i - \phi_j + \phi_{ij} \]  

(1.21)

Antenna-based calibration are generally preferred over baseline-based also because most variations are related to a particular antenna and since the computer capacity requested is reduced instead of the baseline-based. Finally antenna-based calibration can be determined also without the full set of baseline data, very useful when the calibrator is partially resolved.

Amplitude calibration consists in the comparison, for all of the baselines, of the observed visibility amplitude with a radio calibrator. The amplitude calibrator must be a source for which the flux is well-known. It must be not significantly variable, its position must be accurately measured, it must be strong enough to allow its imaging in short time and for simplicity it would be a point source. The most used are: 3C286, 3C147, 3C48 or 3C138. The amplitude calibrator or primary calibrator is typically observed for about 5 minutes at the beginning and at the end of the observation. In practice, when the calibration gains are known from the calibrator, those are applied to the target data in order to refer the flux to the corrected flux scale with respect to the arbitrary scale of uncalibrated data.

Phase calibration is made in order to correct those errors which could compromise the coherence of the signal. As we introduced in the previous sections the visibility function can be expressed as: 

\[ V = |V| \cdot \cos(\phi_T) \]

the total phase delay is the result of various contributions; we have:

\[ \phi_T = 2\pi\nu(\tau_g + \tau_i) + \phi_d + \phi_v \]  

(1.22)

where

- \( \tau_g \) is the time delay between the arrival time of the signals at the two antennas. It is a purely geometric quantity, it is not a frequency function because it assumes that the signal travels in a vacuum.
1 Radio Interferometry

- $\tau_i$ is the delay not frequency dependent also called non-dispersive delay; it is caused by tropospheric refraction, by clock errors between the telescopes and path-length changes in the telescope electronic system.

- $\phi_d$ represents the phase change which is a non linear function of frequency, as an example is the effect of the ionosphere on the signal; it is called dispersive phase delay.

- $\phi_v$ is the additional visibility phase term for extended sources.

In the phase calibration, the causes of the delay are neglected, here the complex gains are calculated according to the equation (1.21) for a specific time in a specific direction. Phase calibrator sources must be the closer to the source and they must be point sources. The reason is that point sources phases are considered to be stable, therefore following the calibrator in various intervals of the time of the observation it is possible to trace the variation of the gain phases. The time interval of observation for the calibrator depends on the observing frequency, e.g. about 20 minutes at 1.4 GHz and about 3 minutes at 22 GHz. Calibration sources are useful for determining temporal variations over time-scales longer than about few minutes; most of them are associated with refraction variations caused by the troposphere and ionosphere. Some kinds of phase variation may be avoided observing in dry and windless days in the case of tropospheric fluctuation or in the night and in the solar minimum in the case of ionospheric variations, these lasts in particular will be treated in more detail in the Chapter 2. The absolute gain of most arrays cannot be measured to better than 5% accuracy.

1.6 Bandwidth

The assumptions of the Fraunhofer diffraction for which the radiation is monochromatic, in astronomy, is not actually true, indeed the radio emission from synchrotron origin is continuum. Since celestial sources are weak, in order to obtain high signal-to-noise, observations are made with finite large bandwidths. As can be seen from the equation (1.5) considering the bandwidth we will have:

$$ R(\tau) \propto E^2 \cos(2\pi \Delta \nu \tau_g), $$

the response is reduced if the bandwidth is large compared to the time delay caused by the separation of the antennas. In theory this effect can be avoided only if the cosine term of the (1.23) is kept small. In terms of the observation this can be done inserting a proper delay, $\tau_i$, between the antennas by adjusting the delay. Thus the cosine term will vary as function of the bandwidth and of the difference between the geometrical and instrumental delay: $\cos(2\pi \Delta \nu (\tau_g - \tau_i))$. 

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1.7 Primary beam

For the effect of the finite bandwidth the fringes are modulated by a sinc-function. The full fringe amplitude is then observed for \( \tau_g = 0 \). The values of \( \tau_g \) for which it is possible to measure fringes can be estimated by this relation:

\[
\frac{\sin \pi \Delta \nu \tau_g}{\pi \Delta \nu \tau_g} \approx 1 - \frac{(\pi \Delta \nu \tau_g)^2}{6} > 0.99
\]

which is valid if \( |\Delta \nu \tau_g| \ll 1 \).

1.7 Primary beam

Another effect that must be considered in the analysis of the interferometric response is the primary beam attenuation. Since the elements of the interferometer are of finite sizes, those have different sensitivity according to the directions of arrival of the radiations.

In terms of visibility this means that, in addition to the term of the finite bandwidth, the visibility function is modulated also by the term of the answer of the single antenna. This effect produces a decrease in terms of sensitivity at the edge of the synthesized field; its angular dimensions are about \( \lambda / D \), where \( D \) is the diameter of the single antenna. The primary beam correction is made after the best quality image has been obtained.

1.8 Sensitivity

The sensitivity is defined as the weakest source of radio emission that can be detected (Wrobel & Walker 1999). For an N elements interferometer the sensitivity can be calculated with the formula:

\[
\Delta I_m = \frac{K}{\sqrt{N(N-1)(N_{IF}T_{int}\Delta \nu_m)}} mJy,
\]

where, \( T_{int} \) is the total on-source integration time in hours, \( \Delta \nu_m \) is the effective continuum bandwidth or spectral-line channel width in MHz, and \( N_{IF} \) is the number of IFs or spectral line channels.

\( K \) is a system constant which expresses the antenna’s parameters, it is given by:

\[
K = \frac{0.12T_{sys}}{\eta_a}
\]

where \( T_{sys} \) is the system temperature, and \( \eta_a \) is the antenna efficiency, which is given by \( A_e / A_g \) where \( A_e \) is the effective area and \( A_g \) is the geometric area.
Figure 1.7:

Since at lower wavelengths the r.m.s fluctuations of the temperature are lower, it is evident that for the same collecting area and system noise a mm image will be more sensitive than an image made at meter wavelength. Finally, the elements for which the interferometry sensitivity can be improved increasing in the apposite way: the bandwidth, the antenna surface or the integration time.

1.9 Very Large Array

The VLA is an aperture synthesis interferometer of the National Radio Astronomy Observatory (NRAO), dedicated in the 1980, located in the Plains of San Agustin, west of Socorro, New Mexico (USA). It consists of 27 radio antennas of 25 m of diameter disposed in a Y-shaped guide rail (fig. 1.7). The arms are 21 km long, they from angles of 120°; the whole structure is rotated of 5° with respect to the North-South direction; without this rotation, the projected baselines in the uv plane would not describe ellipses but segments.
The requested time to completely describe the $uv$ plane is about 8 hours. Baselines extend from 1 to 36 km, the observed wavelengths range from 4 m to 7 mm. The simultaneous number of possible baselines is $N(N - 1)/2 = 351$.

The antenna’s mobility gives the possibility to use four different array’s configurations: A, B, C and D. A and B are the most extended, they are typically used for observations in which high angular resolution is required, while C and D advantage short baselines these are used in the case of large scale and low brightness structures. The telescopes are moved about every four months.

Antennas positions follow a power law according to which the distance (D) of the $n$ antenna from the center of the telescope (Y) is $n^\alpha$ with $\alpha = 1.716$; this is made in order to yield an angular resolution which made easy the comparison of observations made with different frequencies. The beam shape is nearly circular.

In the following tables 1.1 and 1.2 are showed the VLA characteristics for the different observation’s wavelengths.
Table 1.1: Characteristic elements for different configurations: $B_{\text{max}}$, $B_{\text{min}}$ = maximum and minimum antenna separation; $\theta_{\text{syn}}$ = the synthesized beam width (FWHM); $\theta_{\text{max}}$ = the largest scale structure ‘visible’ to the array (http://www.vla.nrao.edu/astro/guides/vlas/current).

<table>
<thead>
<tr>
<th>Configuration</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{\text{max}}(\text{km})$</td>
<td>36.4</td>
<td>11.4</td>
<td>3.4</td>
<td>1.03</td>
</tr>
<tr>
<td>$B_{\text{min}}(\text{km})$</td>
<td>0.68</td>
<td>0.21</td>
<td>0.035</td>
<td>0.035</td>
</tr>
<tr>
<td>Synthesized Beamwidth $\theta_{\text{syn}}(\text{arcsec})$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400 cm</td>
<td>24.0</td>
<td>80.0</td>
<td>260.0</td>
<td>850.0</td>
</tr>
<tr>
<td>90 cm</td>
<td>6.0</td>
<td>17.0</td>
<td>56.0</td>
<td>200.0</td>
</tr>
<tr>
<td>20 cm</td>
<td>1.4</td>
<td>3.9</td>
<td>12.5</td>
<td>44.0</td>
</tr>
<tr>
<td>6 cm</td>
<td>0.4</td>
<td>1.2</td>
<td>3.9</td>
<td>14.0</td>
</tr>
<tr>
<td>3.6 cm</td>
<td>0.24</td>
<td>0.7</td>
<td>2.3</td>
<td>8.4</td>
</tr>
<tr>
<td>2 cm</td>
<td>0.14</td>
<td>0.4</td>
<td>1.2</td>
<td>3.9</td>
</tr>
<tr>
<td>1.3 cm</td>
<td>0.08</td>
<td>0.3</td>
<td>0.9</td>
<td>2.8</td>
</tr>
<tr>
<td>0.7 cm</td>
<td>0.05</td>
<td>0.15</td>
<td>0.47</td>
<td>1.5</td>
</tr>
<tr>
<td>Largest Angular Scale $\theta_{\text{max}}(\text{arcsec})$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400 cm</td>
<td>800.0</td>
<td>2200.0</td>
<td>20000.0</td>
<td>20000.0</td>
</tr>
<tr>
<td>90 cm</td>
<td>170.0</td>
<td>540.0</td>
<td>4200.0</td>
<td>4200.0</td>
</tr>
<tr>
<td>20 cm</td>
<td>38.0</td>
<td>120.0</td>
<td>900.0</td>
<td>900.0</td>
</tr>
<tr>
<td>6 cm</td>
<td>10.0</td>
<td>36.0</td>
<td>300.0</td>
<td>300.0</td>
</tr>
<tr>
<td>3.6 cm</td>
<td>7.0</td>
<td>20.0</td>
<td>180.0</td>
<td>180.0</td>
</tr>
<tr>
<td>2 cm</td>
<td>4.0</td>
<td>12.0</td>
<td>90.0</td>
<td>90.0</td>
</tr>
<tr>
<td>1.3 cm</td>
<td>2.0</td>
<td>7.0</td>
<td>60.0</td>
<td>60.0</td>
</tr>
<tr>
<td>0.7 cm</td>
<td>1.3</td>
<td>4.3</td>
<td>43.0</td>
<td>43.0</td>
</tr>
</tbody>
</table>
### Table 1.2: Sensitivity of the VLA (http://www.vla.nrao.edu/astro/guides/vlas/current/vlas.ps).

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Band Name</th>
<th>System Temperature (K)</th>
<th>Antenna Efficiency (%)</th>
<th>RMS (10 min) Sensitivity (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.073-0.0745</td>
<td>400 cm</td>
<td>1000-10000</td>
<td>15</td>
<td>150</td>
</tr>
<tr>
<td>0.3-0.34</td>
<td>90 cm</td>
<td>150-180</td>
<td>40</td>
<td>1.4</td>
</tr>
<tr>
<td>1.24-1.70</td>
<td>20 cm</td>
<td>35</td>
<td>55</td>
<td>0.056</td>
</tr>
<tr>
<td>4.5-5.0</td>
<td>6 cm</td>
<td>45</td>
<td>69</td>
<td>0.054</td>
</tr>
<tr>
<td>8.1-8.8</td>
<td>3.6 cm</td>
<td>35</td>
<td>63</td>
<td>0.045</td>
</tr>
<tr>
<td>14.6-15.3</td>
<td>2 cm</td>
<td>120</td>
<td>58</td>
<td>0.17</td>
</tr>
<tr>
<td>22.0-24.0</td>
<td>1.3 cm</td>
<td>50-80</td>
<td>40</td>
<td>0.22</td>
</tr>
<tr>
<td>40.0-50.0</td>
<td>0.7 cm</td>
<td>80</td>
<td>35</td>
<td>0.27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>RMS Point-Source Brightness (in 12 hours) (mJy)</th>
<th>Untapered Antenna Sensitivity (Array-D) (mJy)</th>
<th>Peak Primary Beam Size (FWHP) (Jy)</th>
<th>Total Confusing Confusing Source Flux in Primary Beam (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.073-0.0745</td>
<td>15</td>
<td>300</td>
<td>700'</td>
<td>20</td>
</tr>
<tr>
<td>0.3-0.34</td>
<td>0.17</td>
<td>52.0</td>
<td>150'</td>
<td>1.8</td>
</tr>
<tr>
<td>1.24-1.70</td>
<td>0.0066</td>
<td>1.9</td>
<td>30'</td>
<td>0.11</td>
</tr>
<tr>
<td>4.5-5.0</td>
<td>0.0064</td>
<td>1.9</td>
<td>9'</td>
<td>0.002</td>
</tr>
<tr>
<td>8.1-8.8</td>
<td>0.0053</td>
<td>1.5</td>
<td>5.4'</td>
<td>0.001</td>
</tr>
<tr>
<td>14.6-15.3</td>
<td>0.020</td>
<td>6.0</td>
<td>3'</td>
<td>0.0001</td>
</tr>
<tr>
<td>22.0-24.0</td>
<td>0.025</td>
<td>10.0</td>
<td>2'</td>
<td>0.0001</td>
</tr>
<tr>
<td>40.0-50.0</td>
<td>0.030</td>
<td>20.0</td>
<td>1'</td>
<td>-</td>
</tr>
</tbody>
</table>
It is often said that one learns by one’s mistakes. Based upon this criterion, I can claim to have extensive knowledge of low frequency radio astronomy.

W. C. Erickson

2

Low Frequency radio observations

Abstract
Radio window is almost completely transparent from millimeter to meter wavelengths. The window is limited in the mm wavelengths by the presence of a number of absorption bands due to oxygen and water vapor which totally absorb the radiation. On the other hand, in the region of longest wavelengths intervenes the ionosphere which completely reflects the radiation. Radioastronomy started at low frequency, it means a wavelength of about 1 meter. The great improvement, in terms of angular resolution, carried by the big radio interferometers constrained the evolution of the low frequency radio astronomy. There are many reasons for that, first the loss of coherence with baselines longer than 5 km because of the scale of ionospheric motions, second the huge number of natural and man-made interferences, third the rapid phase fluctuations and the small number of calibrator sources, finally the computational and technological limits. The “break of the ionosphere barrier” have been initially done with the implement of the VLA system for meter wavelength observations. It follows a new epoch for the low frequency observations with the project of a new generation of instruments (e.g. LOFAR, LWA and SKA). In this chapter we will describe the difficulties which intervene in low frequency observations but also we explain how these can be overcome.

2.1 Time-line of low frequency radio astronomy

In the following list we will retrace the most important steps of the low frequency radio astronomy.
- 1931-35 Jansky discovers the cosmic radio waves, birth of radio astronomy \((\nu \sim 15-30\, \text{MHz})\).

- 1935-40 Reber, Heneye and Keenan discover the non-thermal emission \((\nu \sim 150\, \text{MHz})\).

- 1942 Hey discovers the solar radio emission \((\nu \sim 50-750\, \text{MHz})\).

- 1946 The first 2 element interferometer was built by Ryle.

- 1946-51 Ryle discovers the discrete cosmic radio sources, then he found radio galaxies and the Super Novae Remnants \((\nu \sim 10-500\, \text{MHz})\).

- 1955 Kraus, Mills, Baldwin et al. made the first all-sky survey \((\nu \sim 80\, \text{MHz})\).

- 1955 Burke, Franklin and Shain discover the first planetary radio emission \((\nu \sim 10-100\, \text{MHz})\).

- 1958-88 Erickson built the Clarke Lake TPT \((\nu \sim 100-1400\, \text{MHz})\).

- 1962-63 Bennett complete the 3C catalog of radio sources \((\nu \sim 160\, \text{MHz})\).

- 1963 Hazard, Schmidt, Sandage et al. discover the quasars \((\nu \sim 178\, \text{MHz})\).

- 1967 First fringes of VLBI \((\nu \sim 20-1400\, \text{MHz})\).

- 1968 Bell discovers the first pulsar \((\nu \sim 81\, \text{MHz})\).

- 1980 Dedication of the VLA

- 1990 The Naval Research Laboratory (NRL) and National Radio Astronomy Observatory (NRAO) implemented the 74 MHz system at the VLA.

- Next generation of radio astronomy instruments include two great projects of low frequency interferometers in the works: LOw Frequency ARray and Long Wavelength Array.

The crucial element which led to the modern radio astronomy is the advent of the long baseline interferometry, with baselines > 10 km, such long baselines imply, in the case of low frequency, the loss of the phase coherence of the wavefront. As we mention in the Chapter 1, coherence gives the fundamental information of the position and structure of the observed source. Loss of coherence is caused by many factors, that will be discussed in more detail in the next sections.
2.2 Ionosphere

Ionosphere is the layer of the atmosphere (at the height of roughly 100-1000 km), in which due to the high concentration of ions and free electrons \( (n_e = 10^4-10^6 \text{ electrons/cm}^3) \) the propagation of radio waves is modified. The ionization of the gas elements is the result of the interaction between the visible and non-visible radiation, coming from the Sun or in part from cosmic rays, with the Earth’s atmosphere and magnetic field.

Ionosphere plays a fundamental role in many radio applications since a radio wave incident in a ionized layer might be completely reflected. The incident radio wave force the free electrons to vibrate at the same frequency of its electric field. If the wave frequency is higher than plasma frequency (see below) the electrons will radiate the wave toward the ground or the over-space. While if the frequency of the incident wave is lower than plasma frequency the propagation of the radiation can not happen, therefore the radiation is totally reflected.

At frequencies below \( \sim 100 \text{ MHz} \), ionosphere affects radio waves via propagation delays, refraction, Faraday rotation, and total internal reflection. The intensity of the Solar radiation depends on the elevation angle of the Sun. Variations of Solar intensity are reflected in terms of different concentrations of free electrons in the ionosphere. For this reason, the properties of the ionosphere show day and seasonal variations, they are also dependent on the geographic latitude and on the geo-magnetic field.

According to the current models the ionosphere consists in a sequence of layers, in which the different composition of ionized particles varies with the atmosphere height. The Total Electron Content is mainly measured with the Global Position System (GPS) techniques.

### 2.2.1 Refraction index.

The propagation of radio waves through the Earth’s ionosphere can be described by considering a model in which the ionosphere is constituted of several layers of plasma with densities and relative positions varying with height. The time dependence would make this problem considerably more complicated than this simplified model implies. The refractive index for an incident wave of frequency \( \nu \) can be written:

\[
\frac{n_{r}}{1} \approx \sqrt{1 - \frac{4\pi e^2 n_e}{m_e \omega^2}} = \sqrt{1 - \left(\frac{\nu_p}{\nu}\right)^2}
\]

where \( n_e \) is the free electron density and \( \nu_p \) is defined plasma frequency. When \( \nu < \nu_p \), the refractive index becomes imaginary, for frequencies lower than \( \nu_p \) there is total reflection. The refraction index is \( \propto \nu^{-2} \), that means that the effect scales with \( \lambda^2 \), therefore it is more important at longer wavelength. Since the plasma frequency is
2 Low Frequency radio observations

function of the free electron numbers, the refraction index of the ionosphere varies with the content of ions in the different layers in which the ionosphere is divided. For the Earth’s ionosphere, the density of free electrons ranges between $10^4$ and $10^6$ electrons/cm$^3$, corresponding to a plasma frequency on the order of $\nu_p \sim 1-10$ MHz. Therefore, in the ionosphere, waves incident on a plasma with frequency below 10 MHz are perfectly reflected.

2.2.2 Absorption

Since the differential percentage of free electrons in different daytimes, the wave may be attenuated in its passage through the ionosphere. The equation which describes the value of "typical" daytime attenuation is function of the inclination angle ($\phi$) through the ionosphere and of the frequency $\nu$ (in MHz); it is given by:

$$A(\nu, \phi) = \frac{2200}{\nu^2 \sqrt{\sin(\phi)^2 + 2h/R}},$$

(2.2)

here $h$ represents the height of the absorbing layer and $R$ is the radius of the Earth, the attenuation is typically expressed in dB. Following [Lawrence & Chivers 1964], this effect is not appreciable in the low frequency bands of the VLA (4 m and 90 cm). Direct measurements reveal levels of about 0.1 dB in the daytime and 0.01 dB in the night. In cases of solar flares, when the ionosphere is highly disturbed these values may reach levels of 2-3 dB; these events persist for about 10 minutes.

2.2.3 Scintillation

Ionospheric scintillation, is the consequence of small-scale variations in the ionospheric electron density, this produces effects of diffraction and scattering of the propagating rays. Ionospheric scintillation is characterized by random temporal fluctuations both in amplitude and in phase of a radio signal. Intensity scintillation is analogue to the twinkling of stars due to variations in atmospheric density caused by turbulence. This strongly depend on the latitude indeed it is severe at the Poles and in the equatorial region after the sunset. At the VLA latitude the scintillation may be at levels from 2% to 20%.

2.2.4 Faraday Rotation

The Faraday rotation produces a rotation of the angle of linear polarization of an electromagnetic wave which propagates through the ionosphere and the interstellar medium because of the interaction between the wave and the magnetic field.

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2.3 Ionospheric barrier

The variation of the angle is described as follows:

\[ \Delta \Phi / \text{rad} = 2.6 \times 10^{-17} \lambda^2 \int n_e H_\parallel dl \]  

(2.3)

where \( n_e \) is the electron density in \( \text{cm}^{-3} \), \( dl \) is the path length in meters and \( H_\parallel \) is the magnetic field along the line of sight in \( \mu \text{Gauss} \).

This can be also expressed as \( \Delta \Phi / \text{rad} = \lambda^2 \text{R.M.} \); where R.M. is called rotation measure.

For studies of polarization in the range between 1 m and 20 cm the correction for ionospheric Faraday rotation must be considered (e.g. AIPS task ‘GPSDL’ by Erickson 1998).

2.3 Ionospheric barrier

The so called ionospheric barrier is the result of the overlap of many phenomena which until now forbidden low frequency interferometric observations at high angular resolution and sensitivity.

Resolution. The turbulent nature of the ionosphere disarrange the phase of the radio waves propagating through it, this might jeopardize the condition for which the wavefront must be plane, therefore the term of coherence is not preserved. Below 100 MHz, the single antennas typically measure phase rotations, rapidly time variant, of about thousand radians. As we argued in the Chapter 1, the interferometer measures the phase difference in order to go back to the phase information, this has values much smaller than those measured after the wave propagation through the ionosphere at frequencies below 100 MHz.

The minimum size of the baseline for which these errors can be allowed is given by the size scale of the Traveling Ionospheric Disturbances (TIDs). In the case of frequencies below 100 MHz the loss of coherence is measured for baselines longer than 5 km.

Now, if we consider that the angular resolution of the interferometer is given by the relationship \( \theta \propto 3437.75\lambda/D \ [\mu\text{rad}] \), we find that for example at 74 MHz for a baseline smaller than 5 km the angular resolution is about 6 arcminutes. Thus, the coherence is preserved to the detriment of the angular resolution (Fig. 2.1).

The confusion problem limits the sensitivity of low frequency observations, this is given by a number of factors. The limited instrumental sensitivity of a single antenna is given by the contribution of the background sources unresolved in the beam. In synthesis imaging, another well known source of confusion are the side-lobes of the relevant number of background sources present in the wide field of view, these limit the dynamic range. Moreover, the classical confusion limit is given when the density of sources brighter than the rms noise becomes high in the area of the synthesized

\[1^{\text{Astronomical Image Processing System}}\]
2 Low Frequency radio observations

beam. All these effects scale with a relation which is proportional to the square of the angular resolution, e.g. the beam area. Therefore the improvement of the angular resolution will lead to the partial solution of the confusion problem.

It is for these reasons that low frequency interferometry has been constrained for the past several decades from the late 1950s.

2.4 The isoplanatic patch size

At low radio frequencies the phase fluctuations are dominated by the effect of the ionosphere. This because, the angular size of the region of the sky illuminated by the primary beam of the interferometer is larger than the region in which the signal traversing the ionosphere maintains constant the phase relationship. The area in which the wavefront is still plane is called **isoplanatic patch**. Therefore, the wide field of view imaged at low frequencies is bigger than that region of the ionosphere which permit to satisfy the condition for which the phase coherence is preserved.

In practice the primary beam illuminates a portion of sky in which the ionosphere behaves as a **variable refractive** medium. The electromagnetic wave propagates through this wedge with different velocities, therefore with variable refractive indexes. This

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**Figure 2.1:** Schematic view of the size scales of ionospheric motions, in correspondence to the baseline dimension for which phase coherence is lost or preserved.
2.5 VLA low frequency observations

This fact in terms of calibration forces the angular distance between the source and the phase calibrator source, the calibrator must be within the same isoplanatic patch of the target source. Since at short wavelengths the isoplanatic size is much larger than the primary beam of the telescope (45’/νGHz) this problem can be neglected, instead at 4m, the primary beam of the VLA is about 12° while the typical isoplanatic size have been measured to be about 4°. Thus, in theory, in order to image the primary beam one calibrator source must be available for each isoplanatic region present in the field of view (Fig. 22). It is evident how the ionosphere (upper) causes a common refractive offset of the apparent source position for a single source but can have a different refractive offset for a source in another direction; while the troposphere causes a refractive offset for the same source as seen by different elements in an array. An analogous phenomena is well known in optical astronomy, where the turbulence introduced by the astronomical seeing, which is given for example by different temperature layers or different wind speeds interacting, distorts and moves the image in various ways such as the ionosphere makes with low frequency radio images. The correction of these optical distortions are based on adaptive optics system, which measures the characteristics of the lens and corrects for it by means of a deformable mirror controlled by a computer. To make a comparison, adaptive optic corrected images reach angular resolution of 30-60 milli-arcsecond at infrared wavelengths, while the resolution without correction is of the order of 1 arcsecond.

Only preliminary measurements have been made of the isoplanatic patch sizes, they are estimated of few degrees across; what emerges in this limited experience is that this size might vary with the ionospheric conditions. Moreover, the calibration technique developed for higher frequencies can not be used with low frequency observation because of the phases change significantly across the field of view, therefore suitable calibration techniques are needed. In the following we will describe the more recent approach used in low frequency observations in order to “break the ionospheric barrier”. 

2.5 VLA low frequency observations

The grow of the technology gave the possibility to realize low frequency observations with angular resolutions lower than 1’. At the VLA it was in the early 1990s that the NRL and the NRAO implemented the 74 MHz system, while the 327 MHz system was already active. Moreover, Kassim et al. (1993) playing on the technique of self calibration (Pearson & Readhead, 1984) demonstrated that the ionospheric effects which limited long baseline interferometry could be contained. Throughout this
2 Low Frequency radio observations

Figure 2.2: Difference in the effects of ionospheric (upper) and tropospheric (lower) phase screen caused by the difference in size scales and the distance of the antennas (Cotton et al. [2004]).

section there will be described the ways of a low frequency observation with the VLA.
Table 2.1: Characteristics of the low frequency receivers of the VLA in Hanning Smoothing Mode.

<table>
<thead>
<tr>
<th>$\nu_{\text{obs}}$ MHz</th>
<th>Correlator mode</th>
<th>IFs</th>
<th>Channels per IF</th>
<th>Bandwidth MHz</th>
<th>separation Ch. kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>74</td>
<td>4</td>
<td>1</td>
<td>64</td>
<td>1.562</td>
<td>24.4</td>
</tr>
<tr>
<td>327</td>
<td>4</td>
<td>1</td>
<td>32</td>
<td>3.125</td>
<td>97.6</td>
</tr>
<tr>
<td>327</td>
<td>4</td>
<td>2</td>
<td>16</td>
<td>6.250</td>
<td>390.6</td>
</tr>
</tbody>
</table>

2.5.1 Line continuous mode

Observations at 90 cm and 4 m exploit the digital correlator in spectral line mode, typically used for spectroscopic observations, keeping the continuous signal. This technique is called “spectral line continuous mode”. In practice, the whole bandwidth is divided in sub-elements, channels. The typical observing mode is with Hanning smoothing, to reduce the ringing of RFI in the system; the bands and the channel width available at the VLA are shown in Tab. 2.1. These strategies are needed in order to avoid the effect of the bandwidth smearing and to excise the Radio Frequency Interferences (RFI). It should be noted that there is a price to pay for observing in continuous line mode; indeed the amount of data is increased by an order of magnitude. After discarding the “edge” channels in the calibration stage, choosing the band centers again in such a way they more or less the 0.75 of the total bandwidth which can be synthesized. This limitation of the system will be alleviated with the upgrade to the Extended Very Large Array (EVLA) in the coming years. Moreover, when using this set-up the cross polarization terms (i.e. LR and RL), which provide information on the linear polarization, are lost.

2.5.1.1 Bandwidth smearing

The principles upon which synthesis imaging are based are strictly valid only for monochromatic radiation. In the section 1.6, we described the effect of the finite bandwidth in interferometric observations, and we showed how the problem could be solved adding a delay instrumental term. However this compensation is incisive only for the radiation relative to the center of the field, the phase tracking center. When radiation from a finite bandwidth is accepted and gridded as if monochromatic, aberrations in the image will result, since the visibility data are processed as though they were all observed at the center frequency $\nu_0$. The net effect is a radial degradation in the resolution and sensitivity of the array. Bandwidth smearing is a radial effect: the sources become more elongated in the
radial direction from the interferometer phase tracking center as their distance from the phase tracking center increases. Figure 2.3 shows a source 7' far from the field center observed at 20 cm. Since bandwidth smearing do not affect the target source, which is supposed to be in the center of the field, it is not a direct problem, but it must be corrected in order to remove correctly side lobes from those sources far from delay tracking center.

These effects can be parameterized by the product of the fractional bandwidth $\Delta\nu/\nu_0$ and the source offset in synthesized beamwidths $\theta/\theta_{HPBW}$. When this product is of the order unity, the chromatic aberration becomes significant.

For example with the VLA at 327 MHz (with bandwidth of 6.2 MHz Tab. 2.1 resolution of 6'' in A configuration) the estimated offset is about 11'' from the center of the field; while at 74 MHz (with bandwidth of 1.5 MHz Tab. 2.1 resolution of 25'' in A configuration) the estimated offset is $\sim 40''$. This effect increases with increasing angular resolution and with the decrease of the frequency.

Since in the multichannel continuum mode the bandwidth is divided in narrower-bandwidth channels and the visibility correlated as referred to many delay centers the bandwidth smearing can be avoided.

2.5.1.2 Radio Frequency Interferences

One of the most serious problem of low frequency interferometry are Radio Frequency Interferences (RFI). These could have different origins: natural or man-made. The first kind is caused by lightning static during summer time observations, or dust particles which attract charged particles in the proximity of antennas. Moreover solar bursts, geo-magnetic storms, ionospheric scintillations are able to produce signals
2.5 VLA low frequency observations

Figure 2.4: Example of uv data at 74 MHz before and after the excision of RFI.

which might be destructive.

The man-made interferences have many origins which reside mainly in the electronic equipments present in the antennas itself. In order to avoid this problem, the first priority is to minimize the amount of RFI generated by the observatory’s computing and digital signal processing electronics.

It has been established a difference in the nature of the RFI at 74 MHz and 327 MHz. The 74 MHz is a band quieter than the 1 m or 20 cm band for which regard external interferences. At 74 MHz the main font of interference has been detected in the 100 kHz oscillators in the bases of each telescope, those generate harmonics at 100 kHz intervals; unfortunately they cannot be shielded easily. These produce in the data the typical “comb”, which is easy to predict and eliminate.

Since at 327 MHz interferences are externally generated for example FAA radar, television and radio emitting antennas, Solar flares etc., these are difficult to be predicted. For this reason a sensitive RFI measurement and monitoring program is essential to this effort.

Sources of radiation which are far away from the position being observed are suppressed by the primary beam effect (Chapter 1, section 1.7), by the sidelobes of the synthesized beam and by the bandwidth smearing (Chapter 1, section 2.5.1.1). However the solar radiation can be $10^{11}$ times stronger than the level being studied in the image, so it may not be adequately suppressed, even if the Sun is tens of degrees away. Since the Sun has a large angular size, and since the bandwidth smearing
selectively suppressed responses from longer spacing, the errors in the image which are caused by the Sun will be very broad. The effects of solar interference will be very much worse on narrow-bandwidth observations, or on observations made using compact configurations. Since low frequency observations need to be made in "line continuous mode", many attention must be paid as regard as the position of the Sun, preferring nighttime observations which are better also for the ionospheric conditions. Another factor of increasing disturbance might take place when the interfering signal is generated in one antenna and transmitted to another (cross-talk). Since it usually occur between close antennas, interferences increase with most compact configurations (C and D for the VLA).

In Fig. 2.4 different scales show how the astronomical signal at 74 MHz is plunged into an amount of RFIs of about 10 kJy (left) and the original astronomical signal can be seen only after a careful procedure of RFI excision (right of Fig. 2.4). Since RFI presents as narrowed-bandwidth phenomena, the spectral line mode is a useful observing method in order to help the excision of RFI; indeed it permits to close off and edit those signals which present strong intensity fluctuations, while preserving the majority of data. A careful data editing can be done, as an example using the AIPS package, by following different methods, interactive or automatic, which let us to select and isolate RFI. The task SPFLG allows to analyze data both LL and RR, for both IFs, baseline by baseline and to flag each RFI channel by channel. The combination of the tasks UVPLT, UVFND and UVFLG, for instance, permits to plot the uv data vs the time, to select the bad time ranges, to understand if the RFI regards one baseline, one or all the antennas and finally to flag them. The automatic task FLGIT selects and eliminates those data which flux is greater than a fixed value calculated throughout a model obtained using few of the better channels. After the RFI excision procedure the amount of flagged data is typically about the 10 - 20%.

For the future generation of telescopes more sophisticated mitigation and excision techniques are needed. Methods such as adaptive filtering, null steering, and automatic blanking are still in the research and demonstration stages of development; therefore high quality sample of the RFI is essential to a good suppression. In this way, Golap et al. (2006) recently developed an interactive partitioning technique that allows the removal of interference, under certain conditions at the calibration-imaging stage.

2.5.2 Wide field imaging

In the Chapter 1 are shown the main passages which lead to obtain the brightness of the sky from the visibility. In order to do that with a simple two-dimensional Fourier inversion two assumptions have been made.

1) All the measurements of the visibility lie in a plane; therefore the $w$ component of
the equation 1.7 could be neglected.
2) The field of view is limited to a small angular region. Those condition are almost satisfied at frequencies higher than 1.4 GHz.

Since the primary beam is large at low frequency two dimensional transform can not be used, three dimensional Fourier transform is needed. The problem of non-complanarity array is usually solved by imaging the curved field with a large number of flat facets as shown in figure 2.5.

This number in C configuration at 74 MHz will be about 50 facets, while it will be 500 for A configuration observations at 327 MHz.

At these frequencies sources more than 30° far from the phase center can be bright enough to cause an high level of side lobe confusion. Therefore an appropriate field, which image the entire primary beam and those bright sources outside this, will allow to image these sources and correctly CLEAN them.

The region which covers the primary beam area is made by a set of overlapping facets, it is called “fly’s eye”. All the other sources outside to the primary beam region, the outliers, are found on an external catalog, typically the NRAO VLA Sky Survey (NVSS, Condon et al. [1998]) and the Westerbork Northern Sky Survey (WENSS, Rengelink et al. [1997]). The facetting approach is AIPS specific and is not the only method to deal with this. In fact for the next generation of high resolution, low frequency instruments the wide-field images will be well beyond the capabilities of facetting.

As we mentioned before, the wide field image introduces two related effects: the isoplanatic patch size problem and the bandwidth smearing of the sources at the edge of the field. In the next sections we will show how those problems could be solved and how the wide field will become an essential element in the ionospheric calibration procedure.

**Figure 2.5:** Scheme of a wide field obtained correcting for the 3D with a multi facets overlapping.
2.6 Calibration

The calibration procedure presents some different aspects for 74 and 327 MHz respectively.

For which regards 327 MHz, it could be considered a “transition” frequency, indeed in some stages the higher frequency reduction techniques are still good. This is true in the case of the amplitude and phase calibration. These are treated as described in section 1.5, therefore the choose of the primary calibrators follows the rules presented before, the most used are 3C48, 3C286 or 3C147.

At 74 MHz the calibration scheme consists in the brief observation of a very bright source every hour for about 5 minutes. A first order of amplitude and phase calibration could be made using a model (an image) of the calibrator source.

The ability of this method to produce a good preliminary model as starting point for self-calibration, resides in the fact that the sky is coherent across the array for short baselines (<5 km). Thus in first approximation we can say that for short baselines the calibration at 74 MHz works as for higher frequencies, while for long baselines self-calibration procedures are needed. Therefore at 74 MHz a good model of calibration can be found if the calibrator source is a bright source, it could be also tens of degrees away from the target, in this aspect 74 MHz differentiates from higher frequency where the phase calibrator source is supposed to be a point source near to the target source. Therefore at 74 MHz, phase solutions are valid only for the sky region near the calibrator source. Moreover these solutions are used at the first order, the phase calibration is completed with self-calibration procedures or ionospheric correction.

The best calibrator source is Cygnus A; its striking flux of about 17 kJy permits to yield calibration trivial; indeed in the majority of cases it is stronger than RFI, so the calibration procedure can be done before the RFI excision stage. Calibrators used in array configurations other than A are: Cas A, the Crab or Virgo A.

Finally, since the scattering from the solar wind, especially during the solar maximum, could affects observations at <40° of radius from the Sun; it is important to avoid this risk making observations away from the Sun.

2.6.1 Bandpass calibration

The spectral line mode is used in order to avoid the chromatic aberration produced by the narrow bandwidths to the strong background sources far from the phase center. The bandpass calibration must be done in order to compensate those changes of antenna gain with frequency, this is made similarly to the amplitude and phase calibration described in section 1.5.

The bandpass calibrator must be a strong source for which the spectrum is flat over frequency of the pass band. Cygnus A is the preferred bandpass calibrator.
2.6 Calibration

Figure 2.6: Answer profile of the bandpass after the calibration for a single VLA antenna.

at 74 MHz, while at 327 MHz, in addition to Cygnus A, one can also uses primary calibrator sources.

The variation across the bandwidth might be ignored if:

$$\frac{\Delta \nu}{\nu} \frac{\theta_{\text{src}}}{\theta_{\text{HPBW}}} \ll 1, \quad (2.4)$$

here the $\frac{\Delta \nu}{\nu}$ is the fractional bandwidth, while $\frac{\theta_{\text{src}}}{\theta_{\text{HPBW}}}$ is the source size expressed in units of synthesized beam.

If we consider Cyg A in the A configuration at 74 MHz, with a typical bandwidth of 1.6 MHz, this quantity is $\sim 0.3$, which means that the visibility might varies of the 30% across the bandpass. This number is even worst at 327 MHz with 6 MHz bandwidth where we calculated 1.4. This means that a model for the bandpass must be used (Fig. 2.6). Fortunately the bandpass function is not strong time-dependent, therefore one calibration per observing run is sufficient.

2.6.2 327 MHz: phase calibration

The phase calibration of 327 MHz data is based on the self-calibration technique. Self-calibration process uses the best available source structure information to improve the antenna phase and, in some cases amplitude gains. The output data set resulting from this operation is used to produce a better image.

In our case the initial source structure is the preliminary model produced in the first stage of calibration. At 327 MHz the model does not need to be too much accurate, but it must include all those sources which are several degrees far from the phase center. For this purpose the NVSS at 1.4 GHz and the WENSS at 327 MHz are sky models.
A multi-field 3D-imaging can be made: the region of the primary beam is obtained overlapping contiguous facets, the “outlier” sources are selected from an external catalog (NVSS) between those sources brighter than a set value far away from the phase tracking center. This is benefited by the fact that the sky is mainly dark. The self-calibration procedure is iterative, it consists in several rounds of imaging–self-calibration.

2.6.3 74 MHz: ionospheric calibration

The distortion of phases, introduced by the ionosphere, given by the variation of the isoplanatic region through the field of view, are one of the most challenging basic theme that interferometry tackled in its history.

Phase calibration of 74 MHz data follows a completely different guideline with respect to the traditional antenna-based calibration techniques developed for higher frequency observations. In the antenna-based calibration all phase distortions can be described by a single time-variable number for each antenna ($\Phi_i(t)$).

With reference to that said before, phase distortions may vary rapidly in 74 MHz observations, on time scales of minutes, for this reason the traditional angle-invariant self-calibration does not work, this is the same reason for which in the initial calibration stage it is useless to observe a phase calibrator. The differential refractive effect is the result of these short time-scale variations (Fig. 2.7). As a consequence those sources, are smeared in the time averaged image therefore they present a lower apparent peak flux, thus a reduced brightness. Figure 2.8 (left) shows that a drop occurs in the number of the sources far from the stronger sources which dominate the calibration (Lane et al. 2004).

Since the phase screens vary across the field of view of the array, there is no operation on the $(u, v)$ data in the preliminary calibration or in self-calibration that can fully remove the effects of the ionosphere; a position-dependent calibration is required. Its application must involve a deconvolution of the image, as an adaptation of self-calibration in which the gain at number of grid points on the sky is determined. The gain at intermediate locations is determined by interpolation. Instrumental effects could be measured independently of the observations, while atmospheric effects can be determined directly from the data. The final model will be the result of several iterations (Cotton 1999).

The application of the position-dependent calibration must be integrated into the imaging processes; in this view W. Cotton and J. Condon developed the FIELD BASED CORRECTION (e.g. Cotton et al. 2004) adopted for the 4m VLA Low-frequency Sky Survey (VLSS). In the following of this section the field-based calibration will be described specifically for the AIPS package.

Here, the visibility phase can be assumed as the contribution of many terms:

$$\phi_{vis} = \phi_{src} + \phi_{ant} + \phi_{ion,low} + \phi_{pec},$$

(2.5)
where $\phi_{\text{src}}$ is the contribution from the sources, the information that we are looking for, $\phi_{\text{int}}$ is the instrumental term, $\phi_{\text{ion,low}}$ and $\phi_{\text{pec}}$ are ionospheric terms. The $\phi_{\text{pec}}$ represent those rapidly varying terms for which there is not an easy parametrization. The $\phi_{\text{ion,low}}$ is associated to those slowly varying terms which can be parametrized by Zernike polynomials \cite{Cotton2004}, which are a set of orthogonal polynomials widely used in the interpretation of optical systems. There are even and odd Zernike polynomials. The even ones are defined as $Z_n^m(\rho, \phi) = R_n^m(\rho) \cos(m \phi)$ and the odd ones as $Z_n^{-m}(\rho, \phi) = R_n^m(\rho) \sin(m \phi)$, where $m$ and $n$ are non-negative integers with $n \geq m$, $\phi$ is the azimuthal angle in radians, and $\rho$ is the normalized radial distance. The radial polynomials $R_n^m$ are defined as

$$R_n^m(\rho) = \frac{(-1)^k (n-k)!}{k! ((n+m)/2-k)! ((n-m)/2-k)!} \rho^{n-2k}$$  \quad (2.6)$$

for $n-m$ even, and are identically 0 for $n-m$ odd. For $m=0$, the even definition is used which reduces to $R_n^0(\rho)$.
Figure 2.8: Images show the 74 MHz primary beam produced using self-calibration (left) and field-based calibration (right) \cite{Lane2004}.

Figure 2.9: Position offsets for a number of bright sources, showed to clarify how the refractive effect of the ionosphere vary across the field of view (by proposals in http://lwa.nrl.navy.mil/VLSS).
2.7 Final considerations.

This technique has been developed for arrays, where baselines are of the order of tens kilometers, for which the variable refraction is a limit in terms of the image size, but for which baselines are short enough that the phase errors produced by the ionospheric motions can be considered to vary approximatively linearly across the array. The image will be shifted with respect to its real position but the image will be not distorted. Therefore it will be possible to attribute precisely a location in “that” time of the source in the field.

The right location of the strongest sources is usually obtained from higher frequency catalogs, e.g. NVSS.

The observation is split in a snapshot, in this way the position offset of the strong sources of the field with respect to the right position can be measured and described as function of the time (see Fig. 2.9). The possible time resolution used for this procedure is typically about 2 minutes.

A crude model of the ionospheric phase screen behaviour can be obtained following a snapshot of simultaneous observations of a number of sources. Since they require relatively few parameters, the Zernike polynomials are useful to fit the offsets in order to describe the ionospheric phase changes. The number of calibrator sources at 74 MHz in VLA observations is about ten, this is enough to constrain the $5^{th}$-term of Zernike polynomial, quadratic in phase and linear in phase gradient. Figure ?? it is shown a phase delay screen model obtained from Zernike polynomials fit. Higher polynomial terms would need more calibrator sources.

In the throughout of the procedure it is possible to set the positions for eliminate those periods of disturbed ionosphere. These are characterized by the defocusing and low amplitude of the calibrator sources or by an excessive residuals to fits.

Finally the figure 2.11 shows how the plane wavefront is deformed after the passage throughout the ionosphere. In practice, during the observation we sample the variation of the ionosphere as differential refraction of the sources; it is only after the field position calibration that we are able to reproduce at a low order of approximation the undistorted wavefront.

2.7 Final considerations.

In this section some additional considerations concerning low frequency observation will be proposed.

The described techniques of self-calibration and field-based-calibration are made possible only because of the conspiracy of an huge number of sources in a field of view which is huge itself.

The majority of the radio astronomical signal is given by synchrotron emission, it is well known that the synchrotron emission spectrum is described with a power law such as: $S(\nu) \propto \nu^{-\alpha}$ with typical $\alpha$’s between 0.5-1.4. It follows that the number of
the sources increase with the decreasing of the frequency, therefore field at 74 MHz will offer a considerable amount of possible calibrators.

At very low frequencies, the system temperature is dominated by the sky background of the emission from our galaxy, whose brightness temperature is \cite{Cane1979}

\[
\left( \frac{T}{K} \right) \approx 900 \left( \frac{\nu}{100 \text{ MHz}} \right)^{-2.55}
\]

between 10 and 100 MHz at high Galactic latitudes. However the presence of many sources in the field could enhance the role of confusion in limiting the sensitivity.

The rms confusion produced by unresolved extragalactic sources in an image having a Gaussian point-source in an image having a Gaussian point-source response with FWHM $\theta$ is \cite{Condon2002}.

\[
\left( \frac{\sigma_c}{\text{mJy beam}^{-1}} \right) \approx \left( \frac{\nu}{100 \text{ MHz}} \right)^{-0.7} \left( \frac{\theta}{\text{arcmin}} \right)^2.
\]

The equation 2.8 indicates the total flux from extragalactic sources within the field of view of a single antenna in an array when the primary beamwidth is substituted

Figure 2.10: Phase delay screen shown as a plane in 3-D viewed from different angles (developed by W. Cotton).
Figure 2.11: Schematic view of the field-based calibration model. Wavefronts (dashed lines) are modified passing throughout the phase screen of the ionosphere (solid line) into nearly gradients projected onto the antennas. Height above the ground of the phase screen represents increasing added phase. The gradient introduced by the ionospheric screen varies with position on the sky inside the large field of view (Cotton et al. [2004]).

for $\theta$. If the entire field of view cannot be imaged accurately, this flux is redistributed randomly throughout the image. The low frequency images are mainly limited by source confusion. Perley & Erickson (1984) in a VLA memo showed that if the baseline is much larger than single antenna, the interferometer response to a large number of point sources in the beam can be regarded as a random variable. Practically, the confusion “noise” is proportional to the r.m.s. sidelobe level of the synthesized beam. The confusion noise can be reduced if the extent that sidelobe responses, of the individual sources in the primary beam, can be identified and removed (Butler & Bastian [1999]).

The field-based-calibration technique corrects the image for the ionospheric distortions using the image itself; other techniques have been tested in order to make Faraday Rotation and phase corrections using the GPS data, for 327 MHz observations (Erickson et al. [2001]). Data from GPS, installed at the VLA site, have been fitted with a simple ionospheric model in order to determine the receiver and transmitter offset. From these parameters Faraday Rotation and interferometer phases can be determined. This technique shows good agreement for correct large-scale ionospheric structures, it is not appropriated for small-scale structures.
Low-Frequency study of two clusters of galaxies: A2744 and A2219

Abstract
Spectral index images can be used to constraint the energy spectrum of relativistic electrons and magnetic field distribution in radio halos and relics, providing useful information to understand their formation, evolution and connection to cluster merger processes.

We present low-frequency images of the two clusters of galaxies: A2744 and A2219, in which a wide diffuse emission is detected. Observations were made with the Very Large Array at the frequency of 325 MHz. For both clusters deep Very Large Array 1.4 GHz observations are available. Combining the 325 MHz and 1.4 GHz data, we obtained the spectral index images and the brightness radial profiles of the diffuse radio emission with a resolution of ~ 1'.

The radially averaged spectral index in A2744 is constant to a value close to $\alpha \approx 1$ up to a distance of 1 Mpc from the cluster center. However, the spectral index image shows the presence of localized regions in which the radio spectrum is significantly different from the average. The observed spectral index variations range from a minimum of $\alpha \approx 0.7 \pm 0.1$ to a maximum $\alpha \approx 1.5 \pm 0.2$. From the comparison of the spectral index with the X-rays data it is found for the first time that the flat spectrum regions of the radio halo tend to have higher temperature. From the comparison of the spectral index with optical it results that in the radio halo, the south-eastern flat spectrum region coincides in projection with a high-velocity group of galaxies. In the case of A2219, the radio emission in the central regions of the cluster is dominated by the blend of discrete sources. The radially averaged radio spectrum is $\alpha \approx 0.8$ in the central region of the cluster and is close to a value of $\alpha \approx 1$ in the radio halo. The lim-
3 Low-Frequency study of two clusters of galaxies: A2744 and A2219

...sensitivity of the 325 MHz image does not allow us to detect all the radio halo structure seen at 1.4 GHz and therefore no constrains on the point-to-point variations of the spectral index have been obtained for this cluster.

3.1 Introduction

In the hierarchical merging scenario, large-scale-structures form as the result of several merger events (e.g. Evrard & Gioia 2002). Clusters of galaxies are the most massive gravitationally bound objects in the Universe and they are structures still forming at the present epoch.

The presence of wide diffuse radio sources associated with the intra-cluster medium (ICM) has been detected in an increasing number of massive, merging, clusters of galaxies. These synchrotron diffuse radio sources are characterized by a typical size of about 1 Mpc, low surface brightness (\(\lesssim 10^{-6} \text{ Jy}/\text{arcsec}^2\) at 1.4 GHz) and steep radio spectrum \(\alpha \geq 1\). They are classified as halos, if they are located in the cluster center, or relics, if they are in the peripheral regions of the cluster (e.g. Giovannini & Feretti 2002). Radio halos and relics demonstrate the existence of relativistic electrons and large scale magnetic fields in the ICM. Many efforts have been done to explain the origin of halos and relics. The relic emission is believed to be caused by the propagation of shock waves produced during cluster merger events. In this case, the radio emission traces the rim of the shock wave in which electrons are injected and/or re-accelerated (e.g. Rottgering et al. 1997; Enßlin et al. 1998). In the case of radio halos, it is required that either the electrons are re-accelerated (primary models: e.g. Tribble 1993; Brunetti et al. 2001; Petrosian 2001; Brunetti et al. 2004; Fujita et al. 2003; Cassano & Brunetti 2005) or continuously injected over the entire cluster volume by hadronic collisions (secondary models: e.g. Dennison 1980; Blasi & Colafrancesco 1999; Dolag & Enßlin 2000). On the other hand, the strength and structure of the magnetic fields have been estimated and simulated with different methods (see e.g. Carilli & Taylor 2002 and Govoni & Feretti 2004 for reviews). Spectral index maps of radio halos and relics are promising tools in the understanding of their formation, evolution and connection to cluster merger processes. Moreover, they provide important information on the energy spectrum of relativistic electrons and magnetic field distribution (Brunetti et al. 2001; Feretti et al. 2004). Re-acceleration models expect a radial spectral steepening in the synchrotron emission from radio halos. The steepening is due to the combined effect of a radial decrease of the magnetic field strength and the presence of a high energy break in the energy distribution of the re-accelerated electron population (Brunetti et al. 2004). In the framework of secondary models, if the spectrum of the primary protons is a power law, the secondary electron-positron pairs have also a power law spectrum, $S(\nu) \propto \nu^{-\alpha}$.
therefore no radial spectral steepening is predicted (Blasi 2001). The possibility to obtain a cut-off in the spectrum of secondary electrons, is to assume a cut-off in the energy distribution of the primary relativistic protons.

**Figure 3.1:** A2744. Left panel: Radio contours of the 325 MHz image obtained with the VLA in BnA configuration are overlaid to the Digitized Sky Surveys optical image of the cluster. The radio image has a resolution of 21" × 11" with a PA = 51°. The noise level is 0.9 mJy/beam. Contours are scaled by $\sqrt{2}$ and the first two levels are -2 and 2 mJy/beam. Right panel: Radio contours of the image at 325 MHz obtained with the VLA in CnB configuration. The resolution is 56" × 44" with a PA = 58°. The noise level is 2.3 mJy/beam. Contours are scaled by $\sqrt{2}$ and the first two levels are -4.6 and 4.6 mJy/beam.

Given the large angular sizes ($\sim 10'$) and steep radio spectrum of halos and relics, suitable spectral index images can only be obtained at frequencies lower than $\sim 1$ GHz. Nowadays Coma (Giovaninni et al. 1993), A2163, A665 (Feretti et al. 2001) and A3562 (Giacintucci et al. 2002) are the only radio halos for which spectral index maps were presented in the literature. In line with primary models, in all these clusters the spectral index maps reveal patchy structure with, in some cases, a trend showing a progressive steepening of the spectrum with increasing distance from the cluster center to the edge.
3.1.1 Scientific motivations

This work is aimed to increase the number of low frequency images and spectral index maps of diffuse emission from cluster of galaxies.

We observed at 325 MHz two cluster of galaxies: Abell 2744 which presents a central radio halo and a peripheral relic and Abell 2219 which hosts a radio halo. The general characteristics of A2744 and A2219 are listed in Table 3.1. They have been already observed with very deep VLA observations at 1.4 GHz in the B and C configurations (Govoni et al. 2001b; Bacchi et al. 2003). These sources are particularly suitable for low frequency studies since they are large and bright and can be imaged by the relatively low sensitive low frequency systems. Moreover since these sources are regular in size a study of the behaviour of radial the spectral index can be done as well as for Coma, A2163, A665 and A3562.

These observations will allow us to look for correlations between spectral index maps and other properties of the cluster (e.g X-ray substructure, optical structure), to apply particles re-acceleration models and to compare these results with those obtained with analogous analysis for other clusters.

The chapter is organized as follows. In Sect. 3.2 we discuss the details about the radio observations and the data reduction. In Sect. 3.3 we present the radio properties of A2744, we show data at 325 MHz, the spectral index map and profile obtained by combining the image at 325 MHz with available data at 1.4 GHz. Moreover we compare the spectral index map with the cluster properties in the X-ray and optical wavelength. In Sect. 3.4 the radio properties of A2219 and the new image at 325 MHz are presented and the spectral index distribution obtained between 325 MHz and 1.4 GHz is shown and discussed. The spectral index behavior in A2744 is analyzed in the framework of a particle re-acceleration model in Sect. 3.5. Finally, in Sect. 3.6 we summarize the results of this study.

Throughout this thesis we adopt: $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.73$ and $\Omega_m = 0.27$.

3.2 Observations and data reduction

Observations were conducted in the 327 MHz band with the Very Large Array\(^2\) in different configurations. Observational parameters are summarized in Table 3.2.

A main problem in low-frequency observations are Radio Frequency Interferences (RFI) that corrupt the data. Particularly in the 327 MHz band, the internal electronic of the VLA gives rise to harmonics that are multiples of 5 and 12.5 MHz. To avoid this problem, a bandwidth of 3.125 MHz is used; since it is narrow it can be placed between

\(^2\)The Very Large Array (VLA) is a facility of the National Radio Astronomy Observatory (NRAO). The NRAO is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.
### 3.2 Observations and data reduction

**Table 3.1:** Clusters properties.

<table>
<thead>
<tr>
<th>Name</th>
<th>$\alpha$(J2000)</th>
<th>$\delta$(J2000)</th>
<th>$z$</th>
<th>kpc/$^\prime\prime$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2744</td>
<td>00:14:19</td>
<td>-30:22:19</td>
<td>0.308</td>
<td>4.502</td>
</tr>
<tr>
<td>A2219</td>
<td>16:40:21</td>
<td>+46:41:16</td>
<td>0.225</td>
<td>3.587</td>
</tr>
</tbody>
</table>

Col. 1: cluster name; Col. 2: and 3: cluster coordinates from NASA/IPAC extragalactic database (NED); Col. 4: redshift (Struble & Rood 1999); Col. 5: arcsec to kpc conversion.

**Table 3.2:** Summary of radio observations.

<table>
<thead>
<tr>
<th>Name</th>
<th>$\alpha$(J2000)</th>
<th>$\delta$(J2000)</th>
<th>$\nu$</th>
<th>$\Delta\nu$</th>
<th>Configuration</th>
<th>Date</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(h\ m\ s)$</td>
<td>$(^\circ\ '\ ''$)</td>
<td>MHz</td>
<td>MHz</td>
<td></td>
<td></td>
<td>hours</td>
</tr>
<tr>
<td>A2744</td>
<td>00:14:15</td>
<td>-30:22:60</td>
<td>321.5, 327.5</td>
<td>3.125</td>
<td>BnA</td>
<td>2004-oct-04</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>321.5, 327.5</td>
<td>3.125</td>
<td>BnA</td>
<td>2004-oct-07</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>321.5, 327.5</td>
<td>3.125</td>
<td>CnB</td>
<td>2004-feb-06</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>321.5, 327.5</td>
<td>3.125</td>
<td>CnB</td>
<td>2004-feb-12</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>321.5, 327.5</td>
<td>3.125</td>
<td>C</td>
<td>2004-may-15</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Col. 1: cluster name; Col. 2, 3: radio pointing position; Col. 4: observing frequency; Col. 5: bandwidth; Col. 6: VLA configuration; Col. 7: date of observations; Col. 8: time of integration.

The location characterized by the so-called “comb” of RFI (Kassim et al. 1993). The observations are usually made in spectral line mode, dividing the bandwidth in several channels. This also reduces the bandwidth smearing, which is very strong at low frequency.

Data were calibrated and reduced with Astronomical Image Processing System (AIPS). We made the amplitude and bandpass calibration with the sources 3C48.
and 3C286 respectively for A2744 and A2219. We used the sources 0025-260 and 1710+460 for the initial phase calibration for A2744 and A2219, respectively.

A careful data editing has been made in order to excise RFI channel by channel. At the end of this procedure 16% of data were flagged in A2744. The data-set of the 2004-oct-4 in BnA configuration was too noisy and it is not presented here. For A2219 flagged data were 10%.

In the final imaging, for A2744 the data were averaged to 7 channels 390 kHz large, while for A2219 they were averaged to 6 channels 488 kHz large. The data were mapped using a wide-field imaging technique, which corrects for distortions in the image caused by the non-coplanarity of the VLA over a wide field of view. A set of small overlapping maps was used to cover the central area of about $\sim 2^\circ$ in radius (Cornwell & Perley 1992). However, at this frequency confusion lobes of sources far from the center of the field are still present. Thus, we also obtained images of strong sources in an area of about $\sim 60^\circ$ in radius, searched in the NRAO VLA Sky Survey (NVSS, Condon et al. 1998) catalog. All these “facets” were included in the CLEAN and used for several loops of phase self-calibration (Perley 1999). The central frequency of the final images is 325 MHz for both A2744 and A2219.

We corrected the final image for the primary beam effect. The VLA gives the possibility to observe with “hybrid” configurations. Namely the antennas on the east and west arms are moved in for the next configuration, but those on the north arm remain extended for a short time; this set-up enhances the view of sources in the southern sky near the galactic center. Since the cluster A2744 is very low in declination, we opted for observations in hybrid configurations. For A2744 the achieved rms sensitivity is 0.9 mJy/beam in BnA configuration and 2.3 mJy/beam in CnB configuration. To improve the u-v coverage and sensitivity we combined the BnA and CnB data sets. The resulting image has a noise level of 1 mJy/beam. For A2219 the achieved sensitivity is 1.7 mJy/beam in both arrays. All these values are somewhat higher than the expected thermal noise levels, because of the contribution of several factors: confusion, broad-band RFI, VLA generated RFI and some others still unknown.

### 3.3 Properties of the cluster A2744

A2744 hosts a central radio halo and a peripheral relic, detected in the NVSS by Giovannini et al. (1999) and confirmed in a deeper observation at 1.4 GHz by Govoni et al. (2001b). The normalized radio and X-ray brightness profiles of the cluster appear to be very similar (Govoni et al. 2001a), indicating that there could be an energetic relation between the X-ray thermal emitting gas and the relativistic radio emitting particles.

Girardi & Mezzetti (2001) and Boschin et al. (2006), derived that galaxies are described by a non-Gaussian velocity distribution. They found two galaxy groups with a
mass ratio of 3:1 which are separated by a line-of-sight velocity of $\Delta V \sim 4000$ km s$^{-1}$. The main one, the low-velocity group, has a velocity dispersion of $\sigma_V \approx 1200 - 1300$ km s$^{-1}$. The secondary one, the high-velocity group, has a velocity dispersion of $\sigma_V \approx 500 - 800$ km s$^{-1}$. Another indication that the cluster is out of the equilibrium is given by [Allen 1998] who found high discrepancies between X-ray masses and lenses masses.

High resolution Chandra X-ray observations confirm the highly disturbed state of the cluster, indeed temperature and brightness gradients have been measured by Kempner & David (2004). They found a main merger in the proximity of the cluster center and a smaller one in the North-Western region, where the presence of a sub-cluster is evident. The peak of the radio halo is located near the cluster X-ray center but the radio halo emission is spread up to the North-Western sub-cluster.

Unfortunately the field of view of Chandra does not include the region where the relic is located.

3.3.1 Low frequency image of A2744

The BnA and CnB configuration images at 325 MHz of A2744 are shown in Fig. 3.1. In the BnA image, which has a resolution of $21'' \times 11''$, we detected both the halo and the relic. This confirms that the emission of the halo and the relic is not due to the blend of discrete sources. There are only three discrete sources in proximity of the radio halo visible in the 327 MHz image, they are labeled with S1, S2 and S3 in the left panel of Fig. 3.1. Out of these sources, S2 could be associated with the member galaxy number 52 in [Boschin et al. 2006], whereas S1 and S3 do not have any obvious optical identification and are likely background objects. We note here that the strong discrete source detected at RA=0$^h$14$^m$.4$^s$ and DEC=−30$^d$24$^m$.41$^s$ in the 1.4 GHz image [Govoni et al. 2001b, see also Fig. 3.3 bottom left panel] is not detected in the 325 MHz high resolution image of Fig. 3.1 (left) and is very faint in the lower resolution image of Fig. 3.1 (right). This is consistent with a source with a spectral index lower than $\alpha < 0.5$.

The CnB configuration image is shown in the right panel of Fig. 3.1. This image has a resolution of $56'' \times 44''$. The combined BnA+CnB array image at 325 MHz (not shown here), produced at intermediate angular resolution ($26'' \times 16''$), has a noise level of 1 mJy/beam, and confirms the structures detected from the image of Fig. 3.1.

The morphology of the diffuse emission is similar to that detected at 1.4 GHz by [Govoni et al. 2001b] for both the halo and the relic, although only the brightest regions of the halo can be seen at 325 MHz due to lower sensitivity of these observations with respect to that at 1.4 GHz. The radio halo in the center of the cluster has a size of $\sim 6'$ ($\sim$1.6 Mpc). The relic is located in the North-Eastern region of the cluster and it shows an elongation in North South direction with a size of $\sim 6' \times 1'$.
3.2 Low-Frequency study of two clusters of galaxies: A2744 and A2219

Figure 3.2: A2744. Left panel: The color-scale represents the spectral index image of A2744 between 325 MHz and 1.4 GHz, with a resolution of 50″×50″. Pixels whose brightness was below 3σ at 325 MHz or 1.4 GHz have been blanked. The cut is driven by the 325 MHz image in most of the points. Contour levels are the radio image at 325 MHz. Contours start at 3.9 mJy/beam (3σ) and scale by √2. The circles indicate the positions of discrete sources, the spectral index in these points is not representative of the radio halo emission. Right panel: The color-scale represents the image of the spectral index uncertainty.

(∼ 1.6 × 0.3 Mpc). Table 3.3 summarizes the main physical parameters obtained from the 325 MHz image both for the halo and the relic. The total flux of the halo, excluding discrete sources, is 218±10 mJy. Using the total flux at 325 MHz and 1.4 GHz, measured in the same area, we calculated an average total spectral index of the halo of α ∼ 1±0.1. The total flux of the relic is 98±7 mJy and its average spectral index is α∼1.1±0.1.

3.3.2 Spectral index analysis of A2744

For the purposes of the spectral analysis we combined the BnA and CnB arrays at 325 MHz and we compared this image with the C+D observation at 1.4 GHz by Govoni et al. (2001b). Images at both frequencies have been restored with the same beam of 50″×50″. The final noise levels are 1.3 and 0.1 mJy/beam for the 325 and 1.4 GHz images, respectively. The spectral index image of A2744, calculated between 325 MHz and 1.4 GHz, is shown in left panel of Fig. 3.2. In the figure we indicate
3.3 Properties of the cluster A2744

Figure 3.3: A2744. Left: Colors represent the images at 325 MHz (top panel) and 1.4 GHz (bottom panel). Contours represent the 325 MHz and 1.4 GHz images. Contours are spaced by $\sqrt{2}$ and start at 3.9 and 0.3 mJy/beam at 325 MHz and 1.4 GHz, respectively. The cross-hatched regions have been excluded from the statistics. Right: Bottom panel shows the radially averaged brightness profiles at 325 MHz (open circles) and at 1.4 GHz (solid circles). Arrows represent 3$\sigma$ upper-limits. The lines represent the fit of an exponential profile to the data (see the text). In the top panel we plot the spectral index radial profile obtained from the brightness profiles.

by circles the discrete sources, whose spectrum is not related to the radio halo. The location of the sources S1 and S3, in regions of very steep radio spectral index, could be interpreted with the fact that these are background objects unrelated with the cluster members. Right panel of Fig. 3.2 shows the spectral index uncertainty, $\sigma_\alpha$. The spectral index image has been obtained by considering only those pixels where
Table 3.3: Radio parameters.

<table>
<thead>
<tr>
<th>Name</th>
<th>type</th>
<th>$S_{325{\text{MHz}}}$ (mJy)</th>
<th>$\alpha$</th>
<th>$B_{eq}$ ($\mu$G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2744</td>
<td>H</td>
<td>218±10</td>
<td>1.0±0.1</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>98±7</td>
<td>1.1±0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>A2219</td>
<td>H</td>
<td>232±17</td>
<td>0.9±0.1</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Col. 1: cluster name; Col. 2: source type (R=relic, H=halo); Col. 3: flux density; the contribution of the point sources have been subtracted; Col. 4: average spectral index between 325 MHz and 1.4 GHz; Col. 5: equipartition magnetic field.

The brightness was above 3σ level at both frequencies. Because of its higher noise, the cut is driven by the 325 MHz image in most of the points. The very different sensitivities of the 325 MHz and 1.4 GHz images introduce a bias in the spectral index image. Indeed, the outermost source regions, whose brightness at 1.4 GHz is at the lowest levels, can only be detected at 325 MHz if their spectrum is steeper than $\sim 1.8$ (see discussion below).

The spectral index image is patchy. The central region has a spectral index of $\alpha \approx 1.05 \pm 0.04$. A prominent region of flatter spectrum is present toward the East, with values of $\alpha \approx 0.7 \pm 0.1$. Another flat spectrum region is located North-West, before the asymmetric halo extension. Beyond this region, the spectrum is steep with values of the spectral index $\alpha \approx 1.5 \pm 0.2$. By comparison of the spectral index image with the error image (Fig. 3.2 left and right panel, respectively) it is evident that most spectral index features are statistically significant.

In the relic, the spectral index trend shows a gradual steepening from values of $\alpha \sim 0.9 \pm 0.1$ to $\alpha \sim 1.6 \pm 0.2$ from the outer to the inner rim. There are not drastic gradients along the main axis, as for the relics in A2256 (Clarke & Enßlin 2006) and A3667 (Rottgering et al. 1997).

We are interested to investigate if there is a systematic variation of the radio halo spectral index with radius as found in the radio halos of Coma (Giovannini et al. 1993), A665 and A2163 (Feretti et al. 2004). The spectral index presented in Fig. 3.2 is fully sampled to within a distance of about one core radius from the cluster center ($r_c \approx 115'' = 520$ kpc; Govoni et al. 2001b). Since the 325 MHz image has a noise level which is an order of magnitude higher than the 1.4 GHz image, only the brightest regions of the radio halo at 325 MHz can be detected beyond this distance. As stated
3.3 Properties of the cluster A2744

Figure 3.4: A2744. Radially averaged brightness profiles for four sectors. Arrows represent 3σ upper-limits. The lines represent the fit of an exponential profile to the data (see the text).

above, the regions of the lowest 1.4 GHz brightness are only detected if their spectrum is steeper than $\alpha > 1.8$, otherwise their 325 MHz emission is too faint to be detected
at the sensitivity limit of the 325 MHz image. As a consequence, a radial steepening of the halo spectrum would be undetectable in the spectral index image, unless it is very strong, to values of $\alpha > 1.8$ in the peripheral regions of the halo. Thus, to improve the statistics and take into account the limits on the 325 MHz emission, we derived the radial trend of the spectral index from the radially averaged brightness profiles at 1.4 GHz and 325 MHz without imposing any cut on the radio images. In order to improve the statistics, we averaged the brightness in ten concentric annuli of $\sim 25^\circ$ in width centered on the radio peak, as shown in top-left panel of Fig. 3.3. The resulting radially averaged brightness and spectral index profiles are shown in the right panel of Fig. 3.3. The errors associated with each point represent the 1σ error on the average value while arrows represent 3σ upper-limits.

Brightness values below a level of 3σ have been considered upper-limits. We fitted the brightness profiles with an exponential law of the form

$$I(r) = I_0 e^{-r/r_\nu} \quad (3.1)$$

and we derived $r_\nu$, the e-folding radius of the brightness profile at both frequencies. It results $r_{325 \text{MHz}} = 293 \pm 23$ kpc and $r_{1.4 \text{GHz}} = 293 \pm 9$ kpc. The e-folding radius at 325 MHz is equal, to within the errors, to that at 1.4 GHz, this implies that the radially averaged spectral index is constant with the increasing distance from the cluster center as shown in the top plot of right panel of Fig. 3.3. Here, the points represent the spectral index obtained from the radially average brightness profiles and the dashed line represents the trend expected from the fit of the exponential law. The radially averaged spectral index in A2744 is constant to a value close to $\alpha \approx 1$ up to a distance of 1 Mpc from the cluster center. This result implies that, although there are significant variations of the spectral index from point-to-point, on average the radio spectrum of the radio halo does not change with radius.

In Fig. 3.4 we show the analysis of the radially average brightness profiles for four cluster quadrants. We note that within the core radius ($r_c = 115''$, red arrows in Fig. 3.3) $\alpha \approx 1$ for all the four quadrants. However, at larger distances from the cluster center the four profiles differ. In agreement with the spectral index image, the steepest spectra are detected in the NW quadrant. Here, the spectral index reaches values of $\alpha \approx 1.6 \pm 0.2$, after some flattening at about 80-120''. The flattest spectra are found in the SE sector, where the values of the outermost regions are constrained by upper limits.

### 3.3.3 Equipartition magnetic field

Under the assumption that a radio source is in a minimum energy condition, it is possible to derive a zero-order estimate of the magnetic field strength averaged over the entire source volume. In the classical equipartition assumption, considering a
3.3 Properties of the cluster A2744

Figure 3.5: Equipartition magnetic field radial profile obtained for the halo in A2744 for $\delta=3$. The profile has been normalized to its value at the center.

The simplified shape of the spectrum of the emitting electrons in the form:

$$N(\varepsilon)d\varepsilon = N_0\varepsilon^{-\delta}d\varepsilon$$  \hspace{1cm} (3.2)

the condition of minimum energy is obtained when the relativistic particle energy density $\varepsilon_{\text{CR}} = \int \varepsilon N(\varepsilon)d\varepsilon$ is approximately equal to the magnetic field energy density $\varepsilon_B = B^2/(8\pi)$. In this assumption the magnetic field can be determined from the radio synchrotron luminosity and the source volume. The volume averaged magnetic field was evaluated within an ellipsoid assuming a magnetic field entirely filling the radio source, equal energy in relativistic protons and electrons, and a range of frequencies in which the synchrotron luminosity is calculated from a low frequency cutoff of 10 MHz to a high frequency cutoff of 10 GHz. For the spectral index of the electron energy spectrum of the halo we adopted the averaged emission spectral index $\alpha \simeq 1.0$ which yields $\delta = 3.0$. For the relic we use $\alpha \simeq 1.1$ which yields $\delta = 3.2$. We estimated an equipartition magnetic field $B_{eq} \sim 0.5 \mu\text{G}$ in the halo and $B_{eq} \sim 0.6 \mu\text{G}$ in the relic.

By assuming a low-frequency cut-off of 10 MHz in the luminosity calculation is equivalent to assume a low-energy cut-off of $\gamma_{\text{min}} \sim 2000$ in the particle energy spectrum. If alternatively we adopt a low-energy cut-off of $\gamma_{\text{min}} = 100$ in the particle energy distribution rather than a low-frequency cut-off in the emitted synchrotron spectrum (e.g. [Brunetti et al. 1997], [Beck & Krause 2005]), we obtain $B'_{eq} \sim 1.0 \mu\text{G}$
in the halo and $B_{eq}^\prime \sim 1.3 \ \mu G$ in the relic.

The radio synchrotron emissivity is given by:

$$j_\nu \propto N_0 B^{(\delta+1)/2} \nu^{-(\delta-1)/2}. \quad (3.3)$$

Under equipartition conditions, if $\gamma_{\text{min}}$ is assumed constant with cluster radius, it is $N_0 \propto B^2$ and therefore:

$$j_\nu \propto B^{(\delta+5)/2}. \quad (3.4)$$

According to this relation, assuming $\delta = 3$, a spherical symmetry and using the de-projected brightness profile at 325 MHz, we obtain the equipartition magnetic field radial trend shown in Fig. 3.5. In each annulus, the de-projected profile has been obtained by subtracting the brightness contribution of the external shells. The magnetic field strength decreases by a factor of two from the cluster center to the halo periphery.

### 3.3.4 Spectral index versus optical and X-ray bands.

On the basis of optical and X-ray data from the Chandra satellite, it has been proposed for A2744 [Girardi & Mezzetti 2001; Kempner & David 2004; Boschin et al. 2006] the following merger scenario: a main merger has been observed, in the proximity of the cluster center, principally along the line of sight, in which two sub-clusters with mass ratio 3:1 and a non-zero impact parameter are interacting. A peripheral merger, with evidence of bow shock in the X-ray image, has been seen in the North-Western region. It involves a less massive sub-cluster and the central region in which the main merger is occurring.

Recent calculations [Cassano & Brunetti 2005] show that a fraction $\sim 10\%$ of the thermal-cluster energy may be channeled in the form of turbulence in case of main (i.e., mass ratio $\leq 5:1$) cluster mergers and this may power up giant radio halos such that observed in the case of A2744. Although the minor mergers cannot directly generate giant radio halos, they may still power the particle acceleration process especially if they happen in clusters which are already dynamically disturbed by previous mergers.

On the basis of the above merger scenario, we investigated if there is any connection between the merger activity observed in the optical and X-ray bands and the spectral index distribution in the radio halo.

The recent optical analysis by [Boschin et al. 2006] based on photometric and spectroscopic data of cluster galaxies shows that A2744 is a very complex cluster from the optical point of view. They pointed out a displacement between the peak of galaxy distribution (see also the weak lensing analysis by [Smail et al. 1997]), and the peak of X-ray emission, as expected in the case of cluster mergers from numerical simulations (e.g. [Roettiger et al. 1997]). The peak of radio emission is displaced with
The two-dimensional distribution of likely members galaxies from Boschin et al. (2006) is shown in contours in the left panel of Fig. 3.6. Galaxies are concentrated in two regions: a main clump, located at the center of the cluster, and a secondary clump is placed at about 2.5′ North with respect to the cluster center. Spectroscopically these galaxies are characterized by two velocity groups separated by line-of-sight velocity of $\Delta V \sim 4000$ km s$^{-1}$. The main one, the low-velocity group, has a velocity dispersion of $\sigma_V \sim 1200 - 1300$ km s$^{-1}$. These galaxies are indicated with open boxes in left panel of Fig. 3.6 and are distributed over the whole cluster. The secondary one, the high-velocity group, has a velocity dispersion of $\sigma_V \sim 500 - 800$ km s$^{-1}$. The galaxies of the high-velocity group are indicated with filled circles in left panel of Fig. 3.6 and are mainly concentrated in the South-West of the cluster. The high-velocity group is likely merging with the main system and being responsible for the strongly disturbed central region. From the comparison with the spectral index image, there is no evident association between optical and spectral features. However, from the radial profiles presented in Fig. 3.4, it is derived that the southern flat spectrum part of the radio halo coincides in projection with the high-velocity group.
of galaxies.

A spatial comparison between the spectral index image of A2744 and the Chandra X-ray brightness image (courtesy of J. C. Kempner, see Kempner & David 2004) is shown in right panel of Fig. 3.6. There is no evident correlation between the radio spectral index and the X-ray brightness features at the cluster center. We note, however, that the region of the NW group has a steep spectrum, while the stripe between the cluster center and the NW group, has a spectrum significantly flatter than the cluster center and the group itself. This is likely the region affected by the collision between the main cluster and the group.

Figure 3.7: Left panel: the grid used to calculate the spectral index-temperature scatter plot is overlayed to the Chandra temperature image (gray scale) by Kempner & David 2004. The contours represent the 325 MHz image. Right panel: Scatter plot of the radio halo spectral index between 325 MHz and 1.4 GHz versus gas temperature.

We further compared the spectral index of the radio halo and the gas temperature image (kindly supplied by J. C. Kempner) of A2744. We averaged the spectral index and the temperature using a grid of rectangular boxes 63olla 63olla in size (see left panel of Fig. 3.7), which is the extraction region of the temperature image (Kempner & David 2004).
3.4 Properties of the cluster A2219

A2219 hosts a giant radio halo detected in the NVSS by Giovannini et al. (1999) and confirmed in a deeper observation at 1.4 GHz by Bacchi et al. (2003). In the cluster center there are three strong radio sources identified as cluster galaxies by Owen et al. (1992). Using Chandra archive X-ray data and optical spectra obtained with the TNG, Boschin et al. (2004) confirmed that the cluster is not dynamically relaxed. Indeed this cluster shows a SouthEast-NorthWest elongation, that is supported by the spatial distribution of the color-selected likely cluster members, the shape of the cD galaxy, the X-ray contours levels, the gradient in the velocity dispersion and the X-ray temperature. From multi-wavelength analysis a very complex scenario results for the dynamic of the merger. Boschin et al. (2004) suggested that the cD galaxy in the center is suffering the consecutive merger of many clumps aligned in a filament for which the projection along the line of view is obliquely oriented. They found a possible confirmation of this scenario in the elongated shape in the South East-North West direction observed in the radio contours map at 1.4 GHz by Bacchi et al. (2003).

3.4.1 Low frequency image of A2219

The A2219 diffuse radio emission at 325 MHz obtained with the VLA in C configuration is shown in the image of Fig. 3.8 (Left panel), which has a sensitivity level of 1.7 mJy/beam and a resolution of $56'' \times 53''$. The obtained sensitivity allows to have good detection of the central region of about $4.5' \sim 950$ kpc) of the halo, in which the morphology is similar to that shown by Bacchi et al. (2003) with a NorthWest-SouthEast elongation. The sensitivity of our observation is not enough to detect more extended regions as seen in low resolution image at 1.4 GHz in Bacchi et al. (2003).

In the Right panel of Fig. 3.8 we show a zoom of the central region of A2219, obtained with the VLA in B configuration, overlaid on the R-band optical image Boschin et al. (2006). The sensitivity level is 1.7 mJy/beam, the resolution is $18'' \times$
Figure 3.8: A2219. Left panel: Radio contours of the image at 325 MHz obtained with the VLA in C configuration. The resolution is $56'' \times 53''$ with $\text{PA} = -85^\circ$. The noise level is 1.7 mJy/beam, contours are scaled of $\sqrt{2}$ where the first two levels are $-3.4$ and $3.4$ mJy/beam. Right panel: Radio contours of the image at 325 MHz obtained with the VLA in B array overlaid onto the optical image (from Boschin et al. 2006). The resolution of the radio image is $18'' \times 16''$ with $\text{PA} = 41^\circ$, the noise level is 1.7 mJy/beam, contours start at 7.5 mJy/beam (4.5$\sigma$ level) and are scaled of $\sqrt{2}$.

It is evident that the radio emission at the cluster center is the blend of three cluster radio galaxies.

The total flux, after the subtraction of discrete sources is $232 \pm 17$ mJy and the average spectral index of the halo, calculated between 325 MHz and 1.4 GHz, is $\alpha \sim 0.9 \pm 0.1$.

The equipartition magnetic field, calculated within a sphere of $330''$ of radius following the classical approach, is $B_{eq} \sim 0.4 \mu G$ (for $\delta = 2.8$) and $B'_{eq} \sim 0.7 \mu G$ (assuming $\gamma_{\text{min}} = 100$) with the approach given in Brunetti et al. (1997).

The main physical parameters of the radio halo in A2219 are summarized in Tab. 3.3.
3.4 Properties of the cluster A2219

3.4.2 Spectral index analysis of A2219

The spectral index image of A2219, with a resolution of 56″×56″ is shown on left panel of Fig. 3.9. The spectral index image, calculated between 325 MHz and 1.4 GHz, have been made using images with the same restored beam, with the same pixel size and considering only pixels with brightness values above 3σ at both frequencies. Right panel of Fig. 3.9 shows the 1 − σ spectral index uncertainty.

The spectral index is $\alpha \sim 0.8\pm0.05$ in the inner 300 kpc, where three blended compact sources are present. At larger distances, the spectral index can be considered representative of the halo emission and ranges between $\alpha = 1.0$ and $\alpha = 1.5$ with a typical uncertainty of 0.2.

In Fig. 3.10 (right), the brightness and the spectral profiles for the halo in A2219 are presented. The notation is the same as in Fig. 3.3. As mentioned before, since in A2219 the radio emission in the center of the halo is dominated by the blend of three point sources, we focused only on the brightness and spectrum at distances more than 500 kpc from the cluster center. The radially averaged spectral index in the radio halo of A2219 is constant within the error, with an average value of $\alpha \simeq 1$. 
Due to the limited information on this radio halo, no attempt was made to derive constraints on the equipartition magnetic field profile for this cluster.

As for A2744, we compare results from radio observations to those from the recent optical analysis based on photometric and spectroscopic data for member galaxies (Boschin et al. 2004). The radio center coincides with the center of the galaxy distribution, i.e. the position of the cD galaxy. The western extension in the radio emission finds an interesting possible correspondence in the western extension of the 2D spatial distribution of bright galaxies (see fig. 9 middle panel of Boschin et al. 2004) and in the East-West direction of the global velocity gradient as recovered from the spectroscopic data.

3.5 Discussion

One of the main difficulties in explaining radio halos arises from the combination of their Mpc size and the short radiative lifetime of the relativistic electrons (about $10^8$ yrs): the diffusion time necessary to these electrons to cover such distances is much larger than their radiative lifetime. Thus, it is required that either the electrons are re-accelerated (primary models) or continuously injected over the entire cluster volume by hadronic collisions (secondary models). Detailed studies of the spectral index in radio halos can provide important inputs to the above models.

For instance, secondary models assume that the relativistic electrons are continuously injected by cosmic ray protons colliding with thermal protons. The cosmic ray protons are accelerated, with a power law energy spectrum, by cluster merger shocks and/or by galactic winds and then they are accumulated over cosmological epochs during the cluster formation (e.g. Berezinsky et al. 1997; Pfrommer et al. 2006 and references therein). The energy spectrum of the relativistic electrons produced by the diffusion of the cosmic ray protons through the ICM is expected to be a smooth power law. In these models, variations in the halo’s magnetic field strength do not produce variation in the radio spectral index. Thus, the constancy of the radially average spectral index profile observed in A2744 and A2219 is in agreement with the expectation of secondary models. However, the patchy structure of the spectral index image in A2744 shows significant variations of the radio halo spectrum over distances as low as $\sim$ 200 kpc. These variations cannot be explained by a featureless power law energy spectrum for the synchrotron electrons and indicate that more complex processes are at work in the ICM.

Primary models assume that the relativistic electrons are re-accelerated over the entire cluster. The particle re-acceleration can be powered by the energy dissipated during cluster mergers. The anti-correlation between spectral index and gas temperature shown in Fig. 3.7 supports the idea that a fraction of the gravitational energy, which is dissipated during major and minor mergers in heating the thermal
3.5 Discussion

plasma, is converted into re-acceleration of relativistic particles and amplification of the magnetic field. In principle the re-acceleration of these particles may occur either via shock acceleration or via turbulent re-acceleration; both scenarios being qualitatively consistent. However, the lack of a clear morphological connection between the presence of shocks in the X-ray image and of synchrotron emitting regions with flatter spectrum would apparently disfavor the shock hypothesis.

Complex spectral energy distributions for the synchrotron electrons are expected in primary models \citep{Brunetti2001}. Therefore, magnetic field variations within the radio halo can give rise to spectral index patterns as those observed in the case of A2744. Primary models assumes that electrons are re-accelerated up to a maximum energy ($\gamma_{\text{max}}$) which marks the balance between acceleration efficiency and energy losses. Above $\gamma_{\text{max}}$ an exponential cut-off in the electron energy spectrum develops. The synchrotron emission extends up to a peak frequency $\nu_{\text{peak}} \propto \gamma_{\text{max}}^2 B$, therefore the lower are $\gamma_{\text{max}}$ and/or $B$, the steeper is the synchrotron spectrum measured between two fixed frequencies. In the re-acceleration scenario via the classical Fermi II mechanism, the systematic energy gain of particles become significant after one acceleration time-scale, $\tau_{\text{acc}}$. If $\tau_{\text{acc}}$ does not depend on the particle energy, the maximum energy of the accelerated particles essentially depends on the ratio between the acceleration efficiency ($\propto \tau_{\text{acc}}^{-1}$) and the particle energy losses:

$$\gamma_{\text{max}} \propto \frac{1}{(B^2 + B_{\text{cmb}}^2)\tau_{\text{acc}}}$$

where $B_{\text{cmb}} = 3.2 \cdot (1 + z)^2 \mu\text{G}$ is the inverse Compton equivalent field\footnote{At the redshift of A2744 $B_{\text{cmb}} = 5.5 \mu\text{G}$}. In this case the peak frequency scales as:

$$\nu_{\text{peak}} \propto \frac{B}{(B^2 + B_{\text{cmb}}^2)^2 \tau_{\text{acc}}}$$

In the simplified hypothesis in which the acceleration efficiency is constant through the cluster and the magnetic field is smaller than the inverse Compton equivalent field, $\nu_{\text{peak}} \propto B$. Thus, we can infer the variations in the magnetic field strength along those directions in which the observed spectral index shows the maximum changes, i.e. in the NW sector of A2744. The shape of the energy spectrum of the synchrotron electrons depends on the adopted value for $\tau_{\text{acc}}$ and on the time for which the electrons are accelerated \citep[e.g.,][]{Ohno2002, Brunetti2004, Brunetti2005, Cassano2005, Cho2006}. Here we calculate the energy distribution of the re-accelerated electrons by assuming $\tau_{\text{acc}} = 10^8\text{yrs}$ (which is appropriate for the emitting particles in radio halos) and by assuming that electrons are re-accelerated for a time-scale $\tau_H \sim 3\tau_{\text{acc}}$ which corresponds to 0.3 Gyrs \citep[in line with the age of radio halos, e.g.][]{Yeh2004}. In Fig. 3.11 we report the
Figure 3.10: A2219. Left: Colors represent the images at 325 MHz (top panel) and 1.4 GHz (bottom panel). Contours represent the 325 MHz and 1.4 GHz images. Contours are spaced by $\sqrt{2}$ and start at 5.1 and 0.48 mJy/beam at 325 MHz and 1.4 GHz, respectively. The cross-hatched regions have been excluded from the statistics. Right: Bottom panel shows the radially averaged brightness profiles at 325 MHz (open circles) and at 1.4 GHz (solid circles). Arrows represent 3σ upper-limits. The lines represent the fit of an exponential profile to the data (see the text). In the top panel we plot the spectral index radial profile obtained from the brightness profiles.

radial behavior of the magnetic field strength obtained by fitting the spectral index profile in the North West quadrant of A2744. In the approximation of constant acceleration efficiency, the magnetic field strength in this quadrant of the cluster is constant, or slightly increasing, up to the core radius ($r_c \approx 115''$) and it decreases by about a factor of two at the halo periphery.
3.6 Summary

We present new VLA images at 325 MHz of the two clusters of galaxies A2744 and A2219, in which a wide diffuse emission was already detected at 1.4 GHz. Combining the 325 MHz and 1.4 GHz data, we obtained the spectral index images and the brightness radial profiles of the diffuse radio emission with a resolution of \( \sim 1' \).

**A2744:** The radio emission of this cluster is characterized by the presence of a radio halo and a peripheral relic. The integrated spectral index between 1.4 GHz and 325 MHz is \( \alpha \approx 1 \pm 0.1 \) in the cluster and \( \alpha \approx 1.1 \pm 0.1 \) in the relic. The radially averaged spectral index in A2744 is close to a value of \( \alpha \approx 1 \) up to 1 Mpc from the cluster center. However, the spectral index image is patchy, showing regions where the spectral index is significantly different from the average. The observed spectral index variations range from a minimum of \( \alpha \approx 0.7 \pm 0.1 \) to a maximum \( \alpha \approx 1.5 \pm 0.2 \).

From the comparison of the spectral index image and radial profiles with the optical data from Boschin et al. (2006) and X-ray data (Kempner & David 2004) it appears that the southern, flat spectrum, part of the radio halo coincides in projection with the high-velocity group of galaxies. There is no evident correlation between the radio spectral index and the X-ray brightness substructures. However, the region of the NW group has a steep spectrum, while the spectrum is flatter between the cluster center and the NW group. Moreover flat spectrum regions tend to have higher temperature. This result supports the idea that a fraction of the gravitational energy, which is dissipated during major and minor mergers in heating the thermal plasma, is converted into re-acceleration of relativistic particles and amplification of the magnetic field.

**A2219:** The radio emission in the central regions of the cluster is dominated by the blend of discrete sources. Therefore, only the outer regions of the radio halo can be studied. The radio spectrum has an average value of \( \alpha \approx 0.8 \) in the central region and a constant profile with \( \alpha \approx 1 \) in the radio halo. The limited sensitivity of the 325 MHz image does not allow us to detect all the radio halo structure seen at 1.4 GHz and therefore no constrains on the point-to-point variations of the spectral index have been obtained for this cluster.
Figure 3.11: Variation of the magnetic field strength in the case of constant acceleration efficiency in the NW quadrant of A2744. The magnetic field strength is normalized to its value at the cluster center.
Giant Radio Sources: 3C35 and 3C223

Abstract
Radio galaxies with a projected linear size $\gtrsim 1$ Mpc are classified as giant radio sources. According to the current interpretation these are old sources which have evolved in a low-density ambient medium. Since radiative losses are negligible at low frequency, extending spectral ageing studies in this frequency range will allow to determine the zero-age electron spectrum injected and then to estimate the synchrotron age of the source. We present Very Large Array images at 74 MHz and 327 MHz of two giant radio sources: 3C35 and 3C223. We performed a spectral study using 74, 327, 608 and 1400 GHz images. The spectral shape is calculated in different positions along the source. The radio spectrum follows a power-law in the hot-spots, while in the inner region of the lobe the shape of the spectrum shows a curvature at high frequencies. Such a kind of steepening is in agreement with the synchrotron aging of the emitting relativistic electrons. In order to estimate the synchrotron age of the sources, the spectra have been fitted with a synchrotron model of emission. It results that 3C35 is an old source of 150 Myr, while 3C223 is a younger source of 70 Myr.

4.1 Introduction
According to the “standard model” of the active galactic nuclei (AGNs), in the center of active galaxies resides a super-massive black hole ($M = 10^8$–10$^9 M_\odot$) powered by an accretion disk surrounded by a torus formed by gas and dust (Scheuer 1974). Classical extragalactic double radio sources originate from highly energetic non-thermal processes occurring in the nucleus of the active galaxies (Rees 1978, Blandford & Rees 1978).
In 10% of AGNs a pair of strong jets forms following the bipolar outflow of relativistic particles expelled perpendicularly to the plane of the disk and extending to great distances from the AGN. The compact, high surface brightness regions at the end of the jets, are called hot spots, these are the impact loci of the flow of relativistic particles and the intergalactic medium. The back-flow material of the jets forms the radio lobes which are presented as diffuse emission in between the hot spots and the nucleus. Finally the lobes of those radio galaxies which have ceased their central activity disappear in the external medium.

A particular class of radio galaxies are giant radio sources (GRS), defined as those objects with a projected linear size $\gtrsim 1$ Mpc$^1$; these are possibly the largest single objects in the Universe. In the complete sample of 3CR radio sources (Laing et al. 1983) about the 6% of sources are giants. They are useful to investigate in many astrophysical problems as an example the evolution of radio sources and the physical conditions of the intergalactic medium (e.g. Ishwara-Chandra & Saikia 1999; Schoenmakers et al. 2001; Lara et al. 2001).

The opened question on these objects is: “why are they so large?” They have intermediate luminosity: $10^{24}$-$10^{26}$ W Hz$^{-1}$. Giant radio sources have core strengths comparable to those of smaller sources of similar total luminosity. Despite their large sizes are unlikely to be caused by stronger nuclear activity. The luminosity-size diagram shows that giant sources are less luminous than expected from the extrapolation of other 3CR sources, consistently with evolutionary scenarios in which giants have evolved from the smaller sources, losing energy as they expand to these large dimensions (Lara et al. 2004). They show a decrease of the luminosity with the source size (Kaiser et al. 1997).

The large intrinsic size can be the result of a long evolution time of the radio source; this implies that in GRS jets are “on” longer than for typical radio sources. The synchrotron ages estimated by Mack et al. (1998) are of about $\sim 10^7$-$10^8$ yr. These values, are comparable with those extrapolated from source evolution models.

It is expected that radio lobes expand and attain the condition of equipartition of the energy density of relativistic particles and magnetic field. Here, the pressure of the relativistic plasma in the lobe equals the pressure of the external environment (Begelman et al. 1984). Another evidence which can justify these huge dimensions is that giant radio galaxies developed in region of low density intergalactic medium, where density is about $10^{-5}$ - $10^{-6}$ cm$^{-3}$ (e.g. Kaiser & Alexander 1999). Moreover, the study of such a kind of sources permitted to Subrahmanyan & Saripalli (1993) to derive the behaviour of the pressure in the intergalactic medium at different redshifts.

Nowadays, it is well accepted that a radio galaxy become a GRS if several factors

$^1$Throughout we adopt $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$ (Spergel et al. 2003). Many radio galaxies have been classified GRS in the past using a different set of cosmological parameters. For this reason some GRS could have a linear size slightly less than 1Mpc.
play together: a low density environment, the old age of the radio source and a core power to provide the jets over Mpc scales.

4.1 Introduction

4.1.1 Scientific motivations.

The non-thermal continuum emission of radio galaxies arises from the synchrotron radiation produced by relativistic particles spiraling in a magnetic field. The synchrotron spectrum is initially described by a pow-law; several mechanisms of particle energy losses intervene to modify the energy of the emitting particles and hence the shape of the emission spectrum ([Jaffe & Perola 1973], hereafter JP; [Kardashev 1962] and [Pacholczyk 1970], hereafter KP). If simple assumptions are satisfied, it is potentially possible to relate the synchrotron spectrum curvature to the radiative age of particles by the measure of the synchrotron spectrum in many independent positions along the lobes.

Due to their large angular size these are well resolved even with a modest angular resolution. Therefore, they are very good candidates for low frequency spectral studies. In this framework, low frequency observations at sub-arcminute resolution would give the possibility to study in detail the emission properties of the radio lobes.

The low-frequency spectral index information is crucial to derive the energy distribution of the radiating electrons, and to study the energy transport from the nucleus to the lobes in these exceptionally large radio sources.

The aim of this study is to produce low frequency images at 74 and 327 MHz of GRS in order to detect the steep spectrum regions of the lobes near to the core. By combining these images with those at higher frequencies (608 MHz and 1.4 GHz) already present in the literature, we will be able to obtain a point-to-point multi-frequency spectral analysis with a resolution of about one arcminute.

We select two classical double giant radio galaxies 3C35 and 3C223. These show a regular FRII morphology ([Fanaroff & Riley 1974]), where the two lobes are extended and well aligned with the hot spots. Their regular structure, the fact that these are powerful and the lobes dominate the emission will allow us to analyze the results with numerical synchrotron models, inferring the break frequency and the radiative ages of the emitting particles. Moreover, since these sources are likely to be old it would be possible to find steep spectrum “relic” regions, such as found by [Lane et al. 2002].

The chapter is organized as follows. In Sect. 4.2 we discuss the details about the radio observations and the data reduction at 74 and 327 MHz. In Sect. 4.3 we present the radio images of 3C35 and 3C223 at 74 and 325 MHz. In Sect. 4.4 we show the spectral index maps and the spectral analysis obtained by combining the images at 74 and 325 MHz with those available in the literature. Here we fit the results with a numerical synchrotron model. Finally, in Sect. 4.5 we summarize the results of this study.
4 Giant Radio Sources: 3C35 and 3C223

<table>
<thead>
<tr>
<th>Name</th>
<th>$\alpha$(J2000) (h m s)</th>
<th>$\delta$(J2000) ($^\circ$ ' '')</th>
<th>$\nu$ MHz</th>
<th>$\Delta\nu$ MHz</th>
<th>Configuration</th>
<th>Date</th>
<th>Duration hours</th>
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<td>327.5 3.125</td>
<td>B</td>
<td>23-NOV-2003</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>327.5 3.125</td>
<td>B</td>
<td>23-NOV-2003</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>327.5-321.5 3.125</td>
<td>C</td>
<td>21-MAR-2004</td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C223</td>
<td>09 39 52.74 +35 53 58.20</td>
<td>73.8 1.562</td>
<td>B</td>
<td>16-DEC-2004</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>73.8 1.562</td>
<td>A</td>
<td>03-MAR-2005</td>
<td>5</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>327.5 6.25</td>
<td>A</td>
<td>16-DEC-2004</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>329.0 6.25</td>
<td>B</td>
<td>03-MAR-2005</td>
<td>5</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

4.2 Radio Data

The two selected giant radio galaxies are 3C35 and 3C223.

3C35 is included in the sample of 47 low redshift ($z < 0.4$) GRS obtained by Schoenmakers et al. (2001) using the Westerbork Northern Sky Survey (WENSS) at 325 MHz of the sky above $+28^\circ$ of declination. They followed the criteria according to which a candidate GRS must have: i) an angular size larger than 5 arcminute, and ii) a distance to the galactic plane of more than 12.5 degree.

3C223 is included in a complete sample of large scale radio sources selected by Leahy & Perley (1991). The sources are drawn by a subset of the complete radio sample defined by Laing et al. (1983) with $z$ less than 0.5.

3C35 and 3C223 have a linear size respectively of $1.1 \text{ Mpc}$ and $1.0 \text{ Mpc}$, using the old set of cosmological parameters ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_0 = 0.5$), while the correspondent values with the new one ($H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, $\Omega_L = 0.73$) are $950 \text{ kpc}$ and $780 \text{ kpc}$.

We observed these two GRS with the Very Large Array at 74 and 327 MHz in several configurations. Observational parameters are summarized in Table 4.1.

4.2.1 Observing strategy

Low-frequency observations are strongly affected by Radio Frequency Interferences (RFI) that corrupt the data.

At 74 MHz most of interferences are due to the 100 kHz oscillators in the bases of each telescope, which generate harmonics at 100 kHz intervals. Unfortunately they cannot be easily shielded and produce in the data the typical “comb”. However this kind of RFI is “easy” to predict and eliminate.
4.2 Radio Data

In the 327 MHz band, the internal electronic of the VLA gives rise to harmonics that are multiples of 5 and 12.5 MHz; to avoid this problem narrow bandwidths are used (Kassim et al. 1993). The observations are usually made in spectral line mode, dividing the bandwidth in several channels. This also reduces for the bandwidth smearing effect, which is very strong at low frequency (see Chapter 2). On the whole, the values of rms sensitivity attained at these frequencies are somewhat higher than the expected thermal noise levels, because of the contribution of several factors: confusion, broad-band RFI, VLA generated RFI.

4.2.2 Data Reduction

Data were calibrated and reduced with Astronomical Image Processing System (AIPS). Since the calibration procedures are different for 74 MHz and 327 MHz, in the following sections we will describe separately the methods applied for the data reduction at 74 MHz and 327 MHz.

4.2.2.1 74 MHz

Both for 3C35 and 3C223 we made the amplitude and bandpass calibration with Cygnus A. In detail we used an image model of Cygnus A retrieved in the web site “http://lwa.nrl.navy.mil/tutorial/VLAmodels”.

A careful data editing operation has been made in order to excise RFI; the percentage of flagged data at the end of this process is about the 13% for both sources. Before the final imaging data were averaged in 8 channels with a resolution of 170.9 kHz.

To produce the final image we used a procedure which makes a correction for the low-order in the ionospheric terms and it performs a "wide-field imaging" (task VLAFM, written and kindly provided by W. D. Cotton). The offsets of the apparent positions of the NVSS sources from their expected positions were computed at time intervals of 2 minutes and corrected in the visibility data. A few data with too large correction were removed for 3C35. We corrected the final image for the primary beam effect.

The final image of 3C35 obtained with VLA data in B configuration has an rms sensitivity of \( \sim 95 \text{ mJy/beam} \).

For the source 3C223 we produced an high resolution image in A configuration, the reached rms sensitivity is \( \sim 43 \text{ mJy/beam} \). A low resolution image has been obtained with data of the VLA in B array, the achieved noise sensitivity is \( \sim 98 \text{ mJy/beam} \). The image obtained with the combination of A and B configurations data has a noise sensitivity of 40 mJy/beam.
4.2.2.2 327 MHz

We made the amplitude and bandpass calibration with the sources 3C48 and 3C286 respectively for 3C35 and 3C223.

An accurate data editing operation has been made in order to excise RFI. At the end of this procedure the 10% of data were flagged in 3C35 and the 3% for 3C223.

For the final imaging, the data of 3C35 were averaged in 5 channels with a resolution of 488.3 KHz, while we averaged in 6 channels of resolution of 781.3 kHz the data of 3C223.

The data were mapped using a wide-field imaging technique, which corrects for distortions in the image caused by the non-coplanarity of the VLA over a wide field of view (the "3-D effect" included in the AIPS task IMAGR). A set of small overlapping maps was used to cover the central area of about $\sim 1.5°$ in radius \cite{CornwellPerley1992}. However, at this frequency confusion lobes of sources far from the center of the field are still present. Thus, we also obtained images of strong sources in an area of about $\sim 80°$ in radius, searched in the NVSS catalog. All these “facets” were included in the CLEAN and used for several loops of self-calibration \cite{Perley1999}. Each observation and single arrays were calibrated, imaged and then combined. We corrected the final images for the primary beam effect.

In particular, for 3C35, we obtain an high resolution image at 327 MHz with the data of the VLA in B configuration, the achieved rms sensitivity is $\sim 1.8$ mJy/beam. A low resolution image has been made with VLA’s observations in C array whit rms sensitivity of $\sim 3.5$ mJy/beam. By combining the data sets of the B configuration and the IF 1 of the C configuration, we improved the uv-coverage and the achieved sensitivity, which is $\sim 1.4$ mJy/beam.

We obtained the high resolution image of 3C223 with VLA observations in A configuration, the reached rms sensitivity is $\sim 0.7$ mJy/beam. The low resolution image with a sensitivity of $\sim 2$ mJy/beam is obtained using data of the VLA in B configuration. To improve the uv-coverage and the sensitivity we combined the data of A and B configuration. The achieved rms sensitivity is $\sim 0.8$ mJy/beam.

4.3 Results

4.3.1 3C35: low frequency images

The source 3C35 is a classical double radio source with a regular FRII structure \cite{FanaroffRiley1974}; its principal characteristics are listed in table 4.2. This source is well known in literature, it has been already studied in radio at 608 and 1400 MHz \cite{vanBreugelJagers1982,Jagers1987,Schoenmakers2000}.

The image shown in fig. 4.1 has been obtained at 74 MHz with the VLA in B configuration. The resolution is $93'' \times 64''$ (PA=-85 °) and the noise level is 95 mJy/beam.
4.3 Results

Table 4.2: Sources properties.

<table>
<thead>
<tr>
<th>Name</th>
<th>$\alpha$ (J2000)</th>
<th>$\delta$ (J2000)</th>
<th>z</th>
<th>kpc/&quot;</th>
<th>LAS</th>
<th>LLS</th>
<th>L$_{178,MHz}$</th>
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<tr>
<td>3C35</td>
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<td>+49 28 35.2</td>
<td>0.0673</td>
<td>1.273</td>
<td>12.5</td>
<td>950</td>
<td>10.26.09</td>
</tr>
<tr>
<td>3C223</td>
<td>09 39 52.74</td>
<td>+35 53 58.2</td>
<td>0.1368</td>
<td>2.393</td>
<td>5.4</td>
<td>780</td>
<td>10.26.89</td>
</tr>
</tbody>
</table>

Col. 1: source name; Col. 2: and 3: source coordinates from NASA/IPAC extragalactic database (NED); Col. 4: redshift by Burbidge & Strittmatter (1972) and 2005SDSS4; Col. 5: arcsec to kpc conversion; Col. 6: largest angular size; Col. 7: largest linear size; Col. 8: Radio luminosity at 178 MHz (Laing & Peacock 1980).

Table 4.3: 3C35 Flux densities and equipartition magnetic field.

<table>
<thead>
<tr>
<th>$\nu$ MHz</th>
<th>Flux density</th>
<th>$\alpha_{73.8-327.4,MHz}$</th>
<th>$B_{eq}$</th>
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<tr>
<td></td>
<td>Total</td>
<td>N lobe</td>
<td>S lobe</td>
</tr>
<tr>
<td>327.4</td>
<td>7.3 ± 0.2</td>
<td>3.8 ± 0.1</td>
<td>3.4 ± 0.1</td>
</tr>
<tr>
<td>73.8</td>
<td>21.1 ± 0.9</td>
<td>12.2 ± 0.4</td>
<td>10.2 ± 0.3</td>
</tr>
</tbody>
</table>

The emission at 74 MHz is stronger in the head of the Northern lobe (N lobe, hereafter).

We produced images at 327 MHz with two different configurations of the VLA (Fig. 4.2). The image showed on the top-left of Fig. 4.2 has been obtained in B configuration, the resolution is 23"×17" with a PA = -85°, while the achieved noise sensitivity is 1.8 mJy/beam. The low resolution image, obtained with the VLA in C array,
is presented in figure 4.2 (top-right), the resolution is $57'' \times 52''$ with a PA=7.5° and the rms sensitivity is 3.5 mJy/beam. In order to improve the uv coverage and the sensitivity we combined the data sets of B and C configuration. The image (Fig. 4.2 bottom) have a resolution of $28'' \times 21''$ with a PA=-86° and the reached sensitivity is 1.4 mJy/beam. These images at 327 MHz confirmed that in the N lobe the radio emission is stronger than in the Southern lobe (S lobe). The hot spot Sud (S hot spot) is slightly shifted with respect to axis of symmetry of the source. In the high resolution image the core has been detected.

For both frequencies 74 and 327 MHz we measured the flux density for the whole source, separately for the two lobes and for the core; all values are listed in table 4.3.

Under the assumption that a radio source is in a minimum energy condition, it is possible to derive a zero-order estimate of the magnetic field strength averaged over the entire source volume. In the classical equipartition assumption, the magnetic field can be determined from the radio synchrotron luminosity and the source volume. The
Figure 4.2: 327 MHz images of 3C35. Top-left: The image obtained with the VLA in B configuration, with a resolution of 23"×17" with a PA=−85°, contours start at (3σ) and scale by $\sqrt{2}$, the first two contours are -5.4 and 5.4 mJy/beam.
Top-right: The image obtained with the VLA in C configuration, with a resolution of 57"×52" with a PA=7.5°, contours start at (3σ) and scale by $\sqrt{2}$, the first two contours are -10.5 and 10.5 mJy/beam. Bottom: The image is obtained with the combined data of B and C configuration of the VLA, the resolution is 28"×21" with a PA=−86°; the noise level is 1.4 mJy/beam, the first two levels of contours are -4.2 and 4.2 mJy/beam they scale by $\sqrt{2}$.
volume averaged magnetic field was evaluated within a cylinder (with radius of about 160 kpc and high ∼ 940 kpc). Assuming a magnetic field entirely filling the radio source, equal energy in relativistic protons and electrons, and a range of frequencies in which the synchrotron luminosity is calculated from a low frequency cutoff of 10 MHz to a high frequency cutoff of 10 GHz. For the spectral index of the electron energy spectrum of the entire source we adopted $\alpha \approx 0.7$ which yields $\delta = 2.4$. We estimated an equipartition magnetic field $B_{eq} \sim 2.0 \mu G$. We consider the volume of the two lobes respectively one half of the total volume. The equipartition magnetic field has been estimated using the same parameters taken above. In the N lobe $B_{eq} \sim 2.1 \mu G$, while for the S lobe we estimated $B_{eq} \sim 2.0 \mu G$.

### 4.3.2 3C223: low frequency images

3C223 is a regular double source with FRII structure; the peculiarity of this source has been pointed out by high-resolution images at 1.4 GHz (see Leahy & Perley 1991) which showed the “V” shaped structure of the northern hot spot. The general characteristics of this source are presented in Table 4.2.

The 74 MHz images shown in figure 4.3 are made by using data of VLA’s observations in A and B configurations. The image on the top-left of figure 4.3 has been obtained in A configuration; the reached rms sensitivity is 43 mJy/beam and the resolution is $25'' \times 24''$ with a PA=58°. The contours of the low resolution image, obtained with the VLA in B array, are shown in the top-right panel of figure 4.3.
Figure 4.3: 74 MHz maps of 3C223. **Top-left:** Image obtained with the VLA in A configuration, with a resolution of $25'' \times 24''$ with a PA=$-58^\circ$, contours start at $(3\sigma)$ and scale by $\sqrt{2}$, the first two contours are -129 and 129 mJy/beam. **Top-right:** The image obtained with the VLA in B configuration, with a resolution of $83'' \times 73''$ with a PA=$-62^\circ$, contours start at $(3\sigma)$ and scale by $\sqrt{2}$, the first two contours are -294 and 294 mJy/beam. **Bottom:** The image is obtained with the combined data of A and B configuration of the VLA, the resolution is $26'' \times 25''$ with a PA=$-61^\circ$; the noise level is 40 mJy/beam, the first two levels of contours are -120 and 120 mJy/beam they scale by $\sqrt{2}$. 
The reached rms sensitivity is 98 mJy/beam and the resolution is $83'' \times 73''$ with a PA=$-62^\circ$. To improve the uv-coverage and the sensitivity, we combined A and B array data sets. Shown in the bottom of fig. 4.3 there is the high resolution image obtained by the combination of A and B array data sets. The resolution is $26'' \times 25''$ with a PA=$-61^\circ$, the achieved noise sensitivity is 40 mJy/beam.

As can be observed by the contours at high resolution, the morphology of the source traced by the higher brightness contours preserves the FRII structure. When we consider lower brightnesses it comes out an extended structure with different orientation axes with respect to the active lobes. There is an hint of low brightness emission also in the image at 1.4 GHz [Leahy & Perley (1991)]. The estimated spectral index is presumably $\alpha \sim 1.3$ (obtained from the spectral index map between 1.4 GHz and 74 MHz not shown here). This structure could be related to a relic lobe.

We produced 327 MHz images with VLA data obtained with the A and B configuration. In the top-left of figure 4.4 are presented the radio contours of the image obtained with the VLA in A configuration. The resolution is $6'' \times 5''$ with a PA=90$^\circ$ and the rms sensitivity reached is 0.7 mJy/beam. On the right of figure 4.4 we have the radio contours of the low resolution image obtained at 90 cm in B configuration. The resolution is $19'' \times 16''$ with a PA=$-80^\circ$ and the reached rms noise is 2 mJy/beam. In the bottom panel of figure 4.4 are presented the radio contours of the high resolution image obtained the combination of the A and B array data. The resolution is $7'' \times 6''$ with a PA=86$^\circ$ and the rms sensitivity reached is 0.8 mJy/beam. Thanks to the high resolution reached it is possible to detect the core and the structure of the N hot spot, which confirms the “V” shape structure seen at 1400 MHz.

For both frequencies 74 and 327 MHz we measured the flux density for the entire source, for the two lobes and for the core; all values are cataloged in table 4.4.

In the classical equipartition assumption, the magnetic field can be determined from the radio synchrotron luminosity and the source volume. We assumed that the volume averaged magnetic field is within a cylinder with radius of $\sim 90$ kpc and high $\sim 840$ kpc. Assuming a magnetic field entirely filling the radio source, equal energy in relativistic protons and electrons, and a range of frequencies in which the synchrotron luminosity is calculated from a low frequency cutoff of 10 MHz to an high frequency cutoff of 10 GHz. For the spectral index of the electron energy spectrum of the entire source we adopted $\delta = 2.0$ which corresponds to $\alpha \simeq 0.5$. $\alpha \sim 0.5$ have been measured in the spectral index map of figure 4.10 in the region of the hot spot. We estimated an equipartition magnetic field $B_{eq} \sim 1.9 \mu$G. Taking the same parameters from above and by considering the volume of the two lobes one half of the total volume, we found $B_{eq} \sim 2.0 \mu$G in the N lobe, while for the S lobe we estimated $B_{eq} \sim 1.8 \mu$G.

Equipartition magnetic field of this source is in agreement with the magnetic field found by [Croston et al.] (2004) with XMM-Newton satellite. They detected X-ray emission from the lobes of the source to inverse-Compton scattering of cosmic mi-
4.3 Results

Figure 4.4: 327 MHz images of 3C223. *Top-left:* The image obtained with the VLA in A configuration, with a resolution of 6″×5″ with a PA=90°, contours start at (3σ) and scale by $\sqrt{2}$, the first two contours are -2.1 and 2.1 mJy/beam. *Top-right:* The image obtained with the VLA in B configuration, with a resolution of 19″×16″ with a PA=-80°, contours start at (3σ) and scale by $\sqrt{2}$, the first two contours are -6 and 6 mJy/beam. *Bottom:* The image is obtained with the combined data of A and B configuration of the VLA, the resolution is 7″×6″ with a PA=86°; the noise level is 0.8 mJy/beam, the first two levels of contours are -2.4 and 2.4 mJy/beam they scale by $\sqrt{2}$. 
4 Giant Radio Sources: 3C35 and 3C223

crowave background photons.

4.4 Spectral analysis

The radio spectra of the majority of the emitting regions of radio galaxies are predominantly power laws. This non-thermal continuum radiation arises from transparent synchrotron emission from relativistic electrons (and perhaps positrons) spiraling in a magnetic field. The non-stationary nature of these spectra was early recognized and investigated in the seminal works of (Kardashev 1962), (Kellermann 1964) and (Pacholczyk 1970). There are two unavoidable mechanisms responsible for electron energy losses in the extended components of a radio source. These are: i) the synchrotron radiation itself and ii) the inverse Compton (IC) scattering with the photons of the cosmic microwave background (CMB):

\[ \frac{d\epsilon}{dt} = c_1(B^2 + B_{CMB}^2)\epsilon^2 \]  

where \( \epsilon \) is the electron energy, \( B \) the magnetic field, and \( c_1 \) is a constant. Inverse Compton losses are represented by \( B_{CMB} \), the equivalent magnetic field associated with the inverse Compton scattering. In the specific case of the CMB photons \( B_{CMB} = 3.25(1 + z)^2 \mu G \), where \( z \) is the source redshift.

In the absence of any constant injection of new electrons or acquisition of energy by re-acceleration, losses result in severe modifications of the initial energy spectrum, particularly in the high energy region. Since high energy electrons emit preferentially at high frequency the most direct consequence of the energy losses is that the synchrotron power law spectrum cuts-off beyond a time-dependent break frequency \( \nu_{\text{break}} \). If there is no expansion and the magnetic field is constant, the frequency \( \nu_{\text{break}} \) depends on the elapsed time since the injection of the electrons, \( t_{\text{syn}} \), through:

\[ t_{\text{syn}} = \frac{1590}{B^2 + B_{CMB}^2} \left[ \frac{1}{\nu_{\text{break}}(1 + z)^{1/2}} \right] \text{ Myrs} \]  

where the break frequency is measured in GHz and the magnetic field in \( \mu G \).

According to various source evolution models, relativistic electrons in different regions of the source are deposited there at different times, so that the frequency break effectively is a clock that indicates the time elapsed since their production.

We fitted the numerical synchrotron model the observed spectra in the lobes of 3C 35 and 3C 223. The errors estimated on the flux measurement include the terms of rms noise and the 3% of the flux for the calibration errors. From the fits we determined the trends of the non-aged spectral index \( \alpha_{\text{inj}} \) and the break frequency \( \nu_{\text{break}} \), that, together with the normalization, are the three free parameters characterizing the aging model. Finally, from the break frequency we determined the radiative age
4.4 Spectral analysis

Table 4.5: 3C35 Images parameters.

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Table 4.6: 3C223 Parameters of images used in the spectral analysis.

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of the relativistic electrons by assuming the equipartition magnetic field. For both sources, the computed equipartition magnetic field is within a factor 2 of \( B_{\text{CMB}} \). This ensures that the synchrotron ages are relatively independent of moderate deviations from the ”minimum energy conditions”.

4.4.1 3C35

We made the spectral analysis using images at four frequencies: 74, 327, 608 and 1400 MHz, see table 4.5.

We produced the spectral index images between 327 and 74 MHz and between 1400 and 327 MHz (Fig. 4.5). The spectral index images have been obtained using images
Figure 4.5: **Left**: Color scale represents the spectral index distribution between 327 and 74 MHz, the resolution is 95”×95”; contours show the radio image at 327 MHz, starting at 30 mJy/beam are scaled by \( \sqrt{2} \). **Right**: Color scale represents the spectral index map calculated between 1400 and 327 MHz, the resolution is 45”×45”; contours show the radio image at 327 MHz, they are scaled by \( \sqrt{2} \), the first level starts at 8 mJy/beam.

with the same beam (Tab. 4.6). The brightness of the two maps have been cut at 3σ level. On the left panel of figure 4.5, is shown the spectral distribution between 74 and 327 MHz. The resolution is 95”×95”. The values of \( \alpha \) vary from \( \alpha \sim 0.6 \pm 0.04 \), in the main parts of the source, to \( \alpha \sim 0.8 \pm 0.07 \) in the most region near to the core. In the spectral index distribution between 1400 and 327 MHz (Fig.4.5, right panel) the resolution is 45”×45”; the image at 1.4 GHz is from the NVSS. Here, the spectral index ranges in a largest interval of values with respect to the 327–74 MHz spectral index map seen above. Indeed, \( \alpha \) is about 0.6±0.02 in the region of the head of the lobes, while it reaches values of \( \alpha \sim 1.7 \pm 0.05 \) in the inner regions of the lobes.

Figures 4.7 and 4.8, are shown the spectra calculated at four frequencies for the N lobe and S lobe respectively. Spectra have been measured using an image cube, which is a composition of images at 74, 327, 608 and 1400 MHz (Tab. 4.6). In figure 4.6 color scale represents the image at 74 MHz with a resolution of 95”×95”, green boxes are the position along the lobes of the source used for the measure of the spectrum. The width of the boxes over the hot spots is about one beam; while for those along the lobes the width is one half of the beam. The contribution of the core has been
Figure 4.6: 3C35: Color scale represents the image 74 MHz, the resolution is 95″×95″; green boxes are the regions in which we calculate the spectrum.

masked in order to have the measure of the diffuse emission in the inner of the lobe. In the plots of figure 4.7 and 4.8, red circles represent the spectra measured in each box along the source. The hot spots are in the first plot, the following plots are those associated to the lobes (the positions are labeled on the bottom-left for each plot).

We fitted the observed spectra with the JP (Jaffe & Perola 1973) synchrotron aging model using Synage ++ software (private report by Murgia). We left as free parameters $\alpha$ injection ($\alpha_{\text{inj}}$), the break frequency $\nu_{\text{break}}$ and the model normalization. The shape of the spectrum, in the case of the hot spots is well described by a power-law, this steepens going from the hot spots to the inner regions of the lobes. The fit, within the errors, give for the two lobes the same minimum frequency: $\nu_{\text{break}} \simeq 0.9$ GHz for the N lobe and $\nu_{\text{break}}$ is $\sim 1.1$ GHz for the S lobe.

We found that, on average, $<\alpha_{\text{inj}}> = 0.5$. However, changes of the injection spectral index from the core to the hot spot can be observed. Within the errors we have the $\alpha_{\text{inj}}$ ranges from $\sim 0.6$ in the hot spots to $\sim 0.4$ near the core. In the case of low frequency spectral studies we have the possibility to measure the variations of the injection spectral index in different positions along the source. Our results showed that variations of the spectral index of injection can be possible during different
Figure 4.7: 3C35: The spectra measured and fitted in different positions along the N lobe.
Figure 4.8: 3C35: The spectra measured and fitted in different positions along the S lobe.
stages of the lifetime of the source. In this case, variations in the mechanism of energy production could be occurred.

The trend of the values estimated from the fit, for $\nu_{\text{break}}$ and $\alpha_{\text{inj}}$, are plotted in the bottom an central panels of figure 4.9 respectively. The synchrotron age of the source has been calculated by using the Eq. 4.2. The values of $\nu_{\text{break}}$ are those obtained by the fit procedure (Fig. 4.9 top panel) and the equipartition magnetic field is in table 4.3. The estimated synchrotron age of 3C35 is about 150 Myr; therefore it is an old source. From the plot of figure 4.9 (top panel) it is clear that the age of the source ($t_{\text{syn}}$) linearly increase with the distance; this is in agreement with a constant expansion velocity. We estimated that the lobes of 3C35 advance in the intergalactic medium at $v_{\text{exp}} \sim 0.01c$.

### 4.4.2 3C223

The spectral analysis has been done using images at 74, 327 and 1400 MHz, see table 4.7. We made the spectral index images between 327 and 74 MHz and between 1400 and 327 MHz (Fig. 4.10). The spectral index images have been obtained using images with the same beam (Tab. 4.8). The brightness of the two images have been cut at 3$\sigma$ level. On the left is shown the spectral distribution between 74 and 327 MHz. The resolution is 26"×26". The spectral index $\alpha$ is about 0.6±0.04 in most of the source.

The spectral index map between 1400 and 327 MHz (right) is at the resolution of 7"×7". The image at 1.4 GHz is by Leahy & Perley (1991). The spectral index increases from $\alpha \sim 0.7±0.02$ in the region of the head of the lobes, to values of $\alpha \sim 1.8±0.04$ in the inner regions of the lobes.

Figures 4.12 and 4.13 show the spectra calculated at three frequencies for the N lobe and S lobe respectively. Spectra have been measured using an image cube, with

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**Table 4.7: 3C223 Images parameters.**

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**Figure 4.9: 3C35** Are plotted with respect to the distance from the core: the fitted values of $\nu_{\text{break}}$ (Bottom); the fitted values for $\alpha_{\text{inj}}$ (center); the estimated synchrotron ages (top).

Images at 74, 327 and 1400 MHz (Tab. 4.8). In figure 4.11 color scale represents the image at 74 MHz with a resolution of $26'' \times 26''$, green boxes are the position along the lobes of the source used for the measure of the spectrum. The width of the boxes is about one beam. The contribution of the core has been masked in order to have the measure of the diffuse emission in the inner of the lobe. In the plots of figures 4.12 and 4.13 red circles represent the spectra calculated in each box along the source.
Table 4.8: 3C223 Parameters of images used in the spectral analysis.

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We fitted the observed spectra with the synchrotron JP model using Synage ++. Since we have three frequencies we left as free parameter the break frequency $\nu_{\text{break}}$ and the model normalization. Assuming that the spectral index does not vary during the lifetime of the source, we used $\alpha_{\text{inj}} = 0.5$. In the case of the hot spots, the shape of the spectrum is quite far from a power-law, it shows an hint of steepening with a value of $\nu_{\text{break}} \approx 4.0-5.0$ GHz. The non-goodness-of-fit might be due to the presence of systematic errors not evaluated here. Moreover, the synchrotron JP model used here is very simple then a more accurate model would be necessary. Both in the N and in S lobe the spectrum steepens going from the hot spots to the core, the minimum break frequency is $\nu_{\text{break}} \approx 2.0$ GHz. We showed the trend of $\nu_{\text{break}}$ with respect to the distance from the core, in the bottom of figure 4.14.

The synchrotron age of the source has been calculated by using the Eq. The values of $\nu_{\text{break}}$ are those obtained by the fit procedure (Fig. 4.14 top panel) and the equipartition magnetic field is in table 4.4. The estimated synchrotron age of the lobes is about 70 Myr. From the plot of figure 4.14 (top panel) the age of the source ($t_{\text{syn}}$) increases with the distance from the hot spots. We estimated that the lobes of 3C223 advance at $v_{\text{exp}} \approx 0.03c$. 

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4.5 Conclusions

In this study we observed with the VLA two giant radio sources: 3C35 and 3C223. The images obtained at 74 and 327 MHz have been presented in this Chapter. A low frequency spectral study has been made by combining our images with those available in the literature. For both sources spectral index images have been obtained at the pairs of frequencies 74-327 MHz and 327-1400 MHz. The spectral index distribution between 74-327 MHz is rather constant along the sources ($\alpha \sim 0.6 \pm 0.04$); while between 327-1400 MHz the spectral index increases from the hot spots ($\alpha \sim 0.6 \pm 0.02$) to the inner regions of the lobes ($\alpha \sim 1.7 \pm 0.04$).

**3C35.** The images at 74 and 327 MHz confirmed the regular FRII morphology of the source. The spectrum has been calculated in different regions along the two lobes of the source (74, 327, 608, 1400 MHz). By fitting the observed spectra with a synchrotron model we obtained a minimum $\nu_{\text{break}} \sim 1.0$ GHz. The $\alpha_{\text{inj}}$ is on average $\sim 0.5$; however the profile shows a systematic variation of $\alpha_{\text{inj}}$ from the hot spots.

**3C223.** Color scale represents the spectral index distribution between 74 and 327 MHz, the resolution is 26”×26”; contours show the radio image at 327 MHz, starting at 12 mJy/beam are scaled by $\sqrt{2}$. Right: Color scale represents the spectral index map calculated between 327 and 1400 MHz, the resolution is 7”×7”; contours show the radio image at 327 MHz, they are scaled by $\sqrt{2}$, the first level starts at 2.4 mJy/beam.

Figure 4.10: 3C223. Left: Color scale represents the spectral index distribution between 74 and 327 MHz, the resolution is 26”×26”; contours show the radio image at 327 MHz, starting at 12 mJy/beam are scaled by $\sqrt{2}$. Right: Color scale represents the spectral index map calculated between 327 and 1400 MHz, the resolution is 7”×7”; contours show the radio image at 327 MHz, they are scaled by $\sqrt{2}$, the first level starts at 2.4 mJy/beam.
to the core. The estimated age for the source is $t_{\text{syn}} \simeq 150$ Myr, it implies that the radio source 3C35 is rather old.

**3C223.** The FRII structure is confirmed by the images at 74 and 327 MHz. Moreover, high resolution images at 74 MHz, shows a low surface brightness structure that could be associated to a relic lobe with a different orientation with respect to the active lobe. We obtained the spectrum in different positions along the lobe at 74, 327 and 1400 MHz. The fit of the spectra with a synchrotron model, assuming $\alpha_{\text{inj}} = 0.5$, yields a minimum $\nu_{\text{break}} \sim 2.0$ GHz. The estimated synchrotron age gives a lifetime of $t_{\text{syn}} \simeq 70$ Myr, which is on average the lifetime extrapolated from the size-sync model [Parma et al. 1999].
Figure 4.12: 3C223. The spectra measured and fitted in different positions along the N lobe.
Figure 4.13: 3C223: The spectra measured and fitted in different positions along the S lobe.
4.5 Conclusions

Figure 4.14: 3C223 are plotted with respect to the distance from the core: the fitted values of $\nu_{\text{break}} (\text{Bottom})$ and the estimated synchrotron ages (top).

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Concluding Remarks

Abstract
This thesis has been focused on low frequency observations of radio halos and giant radio galaxies with the VLA. Combining the new radio images at 74 and 327 MHz with those already existing at higher frequencies, we studied the variations of the synchrotron spectrum point-to-point across these extragalactic radio sources. In this chapter we briefly summarize the main results obtained.

5.1 Summary

5.1.1 The radio halos in Abell 2744 and Abell 2219

We observed with the VLA at 327 MHz the radio halos in the clusters of galaxies A2744 and A2219, for which a wide diffuse radio emission was already imaged at 1.4 GHz (Govoni et al. 2001b and Bacchi et al. 2003). Combining the 327 MHz and 1400 MHz data, we obtained the spectral index images and the brightness radial profiles of the diffuse radio emission with a resolution of ~ 1’ and sensitivity of about 1 mJy/beam.

The radially averaged spectral index in A2744 is constant to a value close to $\alpha \simeq 1$ up to a distance of 1 Mpc from the cluster center. However, the spectral index image shows the presence of localized regions in which the radio spectrum is significantly different from the average. The observed spectral index variations range from a minimum of $\alpha \simeq 0.7 \pm 0.1$ to a maximum $\alpha \simeq 1.5 \pm 0.2$.

In the case of A2219, the radio emission in the central regions of the cluster is dominated by the blend of discrete sources. The radially averaged radio spectrum
5 Concluding Remarks

is $\alpha \simeq 0.8$ in the central region of the cluster and is close to a value of $\alpha \simeq 1$ in the radio halo. The limited sensitivity of the 327 MHz image does not allowed us to detect all the radio halo structure seen at 1400 MHz and therefore no constrains on the point-to-point variations of the spectral index have been obtained for this cluster.

5.1.2 The giant radio sources 3C 35 and 3C 223

We presented new VLA images at 74 MHz and 327 MHz of two giant radio sources: 3C 35 and 3C 223. We performed a spectral analysis by combining 74, 327, 608, 1400 MHz images of matched resolution. We derived the detailed shape of the synchrotron spectrum along the lobes of these giant radio sources.

In the case of 3C 35, by fitting the observed spectra with a synchrotron model we obtained the profiles of the break frequency and injection spectral index along the lobes of the source. The break frequency systematically decreases from the hot spots, where the spectrum is well described by a power law, back to the regions of the lobes nearest to the core, where the spectrum shows an exponential cut off. This behavior in agreement with scenario in which the youngest electrons are injected in the hot spots while the oldest one are left behind by the advancing jets. The age of the source results $t_{\text{syn}} \simeq 150$ Myr and its average expansion speed $v/c \simeq 0.01$.

For 3C 223 we find the same spectral behavior, namely the break frequency decreases from the hot spots to the core of the radio galaxy. However, the synchrotron spectrum of the hot spot is not a simple power law in the considered frequency range. Therefore, in the case of this galaxy we are not able to isolate the zero-age electron population. The age of the source, estimate from the lowest break frequency measured near the core is $t_{\text{syn}} \simeq 70$ Myr and its average expansion speed $v/c \simeq 0.03$.

The radiative ages confirm that 3C 35 and 3C 223 are old radio galaxies.
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