

Faculty of Physics, Astronomy and Applied Computer Science



JAGIELLONIAN UNIVERSITY
IN KRAKÓW

Properties of radio emission and radio spectra of galaxies at low radio frequencies

Wojciech S. Jurasik

A thesis written under the supervision of dr hab. Krzysztof Chyży,
submitted to the Jagiellonian University for the degree of
Doctor of Philosophy in Astronomy

Kraków 2019

Wydział Fizyki, Astronomii i Informatyki Stosowanej,
Uniwersytet Jagielloński

Oświadczenie

Ja niżej podpisany Wojciech Jurusik (nr indeksu: 1039161) doktorant Wydziału Fizyki, Astronomii i Informatyki Stosowanej Uniwersytetu Jagiellońskiego oświadczam, że przedłożona przeze mnie rozprawa doktorska pt. “Properties of radio emission and radio spectra of galaxies at low radio frequencies” jest oryginalna i przedstawia wyniki badań wykonanych przeze mnie osobiście, pod kierunkiem dr hab. Krzysztofa Chyżego. Pracę napisałem samodzielnie.

Oświadczam, że moja rozprawa doktorska została opracowana zgodnie z Ustawą o prawie autorskim i prawach pokrewnych z dnia 4 lutego 1994 r. (Dziennik Ustaw 1994 nr 24 poz. 83 wraz z późniejszymi zmianami).

Jestem świadom, że niezgodność niniejszego oświadczenia z prawdą ujawniona w dowolnym czasie, niezależnie od skutków prawnych wynikających z ww. ustawy, może spowodować unieważnienie stopnia nabytego na podstawie tej rozprawy.

Kraków, dnia

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podpis doktoranta

To memory of my father

Acknowledgements

I am immensely grateful to my PhD supervisor dr hab. Krzysztof Chyży for his support, and effort over the years of my studies. I would like to express my deepest gratitude to him for all his knowledge and experience that he has been willing to share with me, suggestions and inspiring discussions.

I would also like to thank dr hab. Marek Jamroz for his comments and advices, which had important influence on the final shape of this dissertation.

I would like to thank my wife Natalia, for her trust in me and her constant support during the preparation of this thesis. She made countless sacrifices to help me get to this point. I would like to express my sincere gratitude to my Mom for endless support and understanding that made the completion of this thesis possible.

I am also thankful to staff of the Astronomical Observatory of the Jagiellonian University, particularly members of Department of Radioastronomy and Space Physics, for providing friendly environment during my studies, sharing knowledge, and opportunity to be a part of different projects.

This research has made use of data from the LC0_043 project carried out with the Low Frequency Array (LOFAR), and from the Multifrequency Snapshot Sky Survey (MSSS).

Finally, I acknowledge the financial support from the Polish National Science Centre grant No. 2013/09/N/ST9/02511.

Abstract

In this work, observations and 3D numerical modelling of radio emission of nearby galaxies at low radio frequencies are presented. Using LOFAR interferometer a nearby galaxy NGC 6946 was observed for the first time at 144 MHz. I report a discovery of a large synchrotron envelope extending out to radius of 18 kpc, i.e. further than the optical and high-frequency radio emission of this object. Analysis of the envelope emission indicates existence of population of low-energy cosmic-ray electrons (CREs), which can be transported by diffusion far away from their acceleration sites in spiral arms. Furthermore, the radial profile of synchrotron emission of NGC 6946 at 144 MHz reveals two breaks. The first break at radius of about 3 kpc corresponds with the transition between thin and thick galactic disks, while the second one between the inner and outer disks at about 9 kpc, can be ascribed to sudden disappearance of star-forming regions and sources of CREs. The integrated spectrum of NGC 6946 does not flatten towards low frequencies, excluding strong free-free absorption, while the local spectrum from the central parts reveals a spectral turnover below 300 MHz, indicating local absorption presumably caused by ionized gas within HII complexes.

For a better understanding of the low-frequency radio spectra, I developed a 3D numerical model of emission of star-forming galaxies, including the radiative transfer equation and taking into account the projection effects. I show that the modelling of radio emission from galaxies in the simple form of well-mixed thermal and synchrotron media is not sufficient to reproduce the actual spectra of galaxies. It is necessary to introduce galactic halos, their size, intensity, and synchrotron spectral index, strongly influence the model spectra. The clumpy ionized gas with different filling factor introduced in the model, can further affect the modelled galactic spectra, however, it does not change the frequency of the spectral turnover caused by free-free absorption.

Subsequently a thorough modelling of M 51- and M 82-like galaxies was performed. The modelled integrated spectra of M 51-like galaxies predict the free-free absorption effects to appear only at frequencies below of 20 MHz, while in the spectra of starburst galaxies, such as M 82, a flattening due to absorption is visible between 200 - 400 MHz, depending on the inclination angle. The curvature of synchrotron spectrum introduced in modelling, can explain the apparent contradiction between the free-free absorption effects observed in the starburst galaxies and the lack of correlation between the curvature of radio spectra and the viewing angle of the typical galaxies. Furthermore, M 51-like galaxies with simple power-law-like integrated spectra, can locally reveal significantly curved spectra. Therefore, interpretation of integrated spectra of galaxies cannot be carried out properly without supplementary data on the properties of the local interstellar medium within the galaxies.

According to my modelling, the effects of free-free absorption can be distinctly seen in the local spectra from the central parts of the M 51-like galaxies as turnovers around 100 - 200 MHz in the edge-on ones, and as less distinct turnovers below 100 MHz with spectral rising towards low frequencies for the low-inclined objects. Much stronger effects can be seen in the local spectra from the core of M 82-like galaxies as strong turnovers at frequencies about 1000 MHz for the highly inclined galaxies, and about 500 MHz for the weakly inclined galaxies. Consequently, it is possible to observe much stronger effects of free-free absorption in more distant galaxies with higher star-formation rates.

The presented modelling predicts also a possible influence of the Milky Way foreground ionized gas on all external galactic spectra at frequencies below 10 MHz. Such an effect could only be confirmed using observations with radio interferometers located in space or ideally on the surface of the Moon, far away from the influence of the Earth's ionosphere and electromagnetic pollution.

Streszczenie

W niniejszej pracy przedstawione są obserwacje i trójwymiarowe (3D) modelowanie numeryczne emisji radiowej bliskich galaktyk na niskich częstotliwościach radiowych. Używając interferometru LOFAR po raz pierwszy przeprowadzono obserwacje galaktyki NGC 6946 na częstotliwości 144 MHz. Ujawniły one rozległą otoczkę synchrotronową, rozciągającą się aż do promienia 18 kpc, tj. dalej niż emisja optyczna galaktyki i jej wysokoczęstotliwościowa emisja radiowa. Analiza świecenia tej otoczki wskazuje na istnienie populacji nisko-energetycznych elektronów promieniowania kosmicznego (EPK), które w procesie dyfuzji przemieszczają się daleko od miejsc ich przyśpieszania w ramionach spiralnych. Ponadto profil radialny emisji synchrotronowej NGC 6946 na częstotliwości 144 MHz uwidoczniał dwa załamania. Pierwsze załamanie, na promieniu około 3 kpc, odpowiada przejściu pomiędzy tzw. cienkim a grubym dyskiem galaktyki. Natomiast drugie załamanie, pomiędzy wewnętrznym a zewnętrznym dyskiem, w odległości około 9 kpc od jądra można wyjaśnić nagłym zanikiem obszarów gwiazdotwórczych oraz źródeł EPK. Zintegrowane widmo radiowe NGC 6946 nie pokazuje wypłaszczenia w kierunku niskich częstotliwości co wyklucza silną absorpcję termiczną. Natomiast lokalne widmo, z centralnej części galaktyki łałamuje się poniżej 300 MHz wskazując na lokalną absorpcję, prawdopodobnie spowodowaną zjonizowanym gazem w kompleksach HII.

W celu lepszego zrozumienia niskoczęstotliwościowych widm radiowych, stworzyłem numeryczny model 3D emisji gwiazdotwórczych galaktyk, który uwzględnia równanie transferu promieniowania radiowego biorąc pod uwagę efekty projekcji. Okazuje się, że prosty model galaktyki w formie dobrze wymieszanego termicznego i synchrotronowo świecącego ośrodka nie jest w stanie odtworzyć rzeczywistych widm galaktyk. Potrzebne jest uwzględnienie galaktycznego halo, jego rozmiar, natężenie oraz synchrotronowy indeks spektralny, silnie wpływają na wyniki modelowania. Wprowadzenie zjonizowanego gazu w formie kłaczkowatej, o różnym współczynniku wypełnienia również wpływa na modelowane widma galaktyk, ale nie zmienia ono załamań w widmach spowodowanych absorpcją termiczną.

Następnie wykonane zostało kompleksowe modelowanie galaktyk podobnych do M 51 i M 82. Modele zintegrowane widma galaktyk typu M 51 przewidują efekty absorpcji termicznej tylko poniżej częstotliwości 20 MHz. Natomiast w galaktykach o silnej aktywności gwiazdotwórczej, jak M 82, załamania widm spowodowane absorpcją termiczną widoczne są pomiędzy 200 a 400 MHz, w zależności od nachylenia dysku galaktyki. Poprzez wprowadzenie do modelowania zakrzywionych widm synchrotronowych udało się wyjaśnić pozorną sprzeczność pomiędzy obserwowanymi silnymi efektami absorpcji termicznej w galaktykach silnych gwiazdotwórczo, a brakiem korelacji pomiędzy krzywizną widm radiowych a nachyleniem dysków dla typowych galaktyk. Ponadto modele pokazują, że obiekty typu M 51, które charakteryzują się prostym zintegrowanym widmem potęgowym, mogą lokalnie ujawniać znacząco zakrzywione widma. Dlatego interpretacja zintegrowanych widm radiowych galaktyk nie może być właściwie przeprowadzona bez uzupełniających danych o lokalnych własnościach ośrodka międzygwiazdowego.

Zgodnie z moim modelowaniem, efekty absorpcji termicznej są wyraźnie widoczne w (lokalnych) widmach centralnych części galaktyk typu M 51, jako załamania pomiędzy 100 a 200 MHz dla silnie nachylonych dysków galaktyk. Natomiast dla galaktyk o mniejszym nachyleniu dysku widoczne są mniej wyraźne załamania widma poniżej 100 MHz z podnoszącym się widmem ku niższym częstotliwościom. Znacznie silniejsze efekty absorpcji widoczne są w widmach z jądra galaktyk typu M 82 oglądanych pod dużym kątem, jako wyraźne załamania na częstotliwości około 1000 MHz. Dla mniej nachylonych dysków tych galaktyk załamania widm występują na około 500 MHz. W konsekwencji, możliwe jest zaobserwowanie znacznie silniejszych efektów absorpcji promieniowania w odległych galaktykach z silniejszymi procesami gwiazdotwórczymi.

Przedstawione modelowanie przewiduje również możliwy wpływ zjonizowanego gazu Drogi Mlecznej na widma radiowe wszystkich galaktyk obserwowanych poniżej 10 MHz. Taki efekt absorpcji może zostać potwierdzony jedynie w obserwacjach wykonanych interferometrami radiowymi umieszczonymi w przestrzeni kosmicznej, a najlepiej na powierzchni Księżyca, z dala od wpływu ziemskiej jonosfery i zanieczyszczeń elektromagnetycznych.

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Acronyms

CASA Common Astronomy Software Applications

CREs Cosmic-Ray Electrons

EM Emission Measure

GMRT Giant Meterwave Radio Telescope

IGM Intergalactic Medium

ISM Interstellar Medium

LOFAR Low Frequency Array

LTE Local Thermal Equilibrium

MSSS Multifrequency Snapshot Sky Survey

RFI Radio Frequency Interference

RM Rotation Measure

SNR Supernova Remnant

(U)LIRG (Ultra) Luminous Infrared Galaxy

VLA Very Large Array

WSRT Westerbork Synthesis Radio Telescope

CHAPTER 1

Introduction

1.1 Motivations for low-frequency radio studies of galaxies

The radio continuum emission of star-forming galaxies were investigated extensively at high radio frequencies above 1000 MHz throughout the last decades. It is believed that the radio emission of normal star-forming galaxies originates from two processes: the free-free emission (thermal emission) from HII regions associated with most recent star formation sites, and the synchrotron (non-thermal) radiation of cosmic-ray electrons (CREs) accelerated in supernova remnant (SNR) shock fronts in the ambient galactic magnetic field (Condon 1992). The synchrotron emission, having steep spectrum $\propto \nu^{-\alpha_{nt}}$ ($\alpha_{nt} \approx 0.8$, Niklas et al. 1997b), dominates the free-free emission at frequencies below 30 GHz, and typically constitutes about 90% of the total galactic radio emission at 1.4 GHz (e.g. Han 2017), while the free-free emission has a much flatter spectrum ($\propto \nu^{-0.1}$) and becomes more important at higher frequencies.

Nearby spiral galaxies have been little studied at low frequencies (≤ 300 MHz) due to technical difficulties and challenges of low-frequency radio interferometry (see Section 1.6). The first systematic low-frequency survey of galaxies was performed by Israel & Mahoney (1990), who used the Clark Lake Radio Observatory TPT array (called the TPT due to teepee-shaped antennas) at 57.5 MHz to observe 133 galaxies. This study was limited by angular resolution ($\approx 7'$) and therefore could analyse only the integrated flux densities of 68 galaxies. The measured 57.5 MHz flux densities were systematically lower than the relevant extrapolations from the higher frequencies. The authors postulated that the lower observed flux densities at 57.5 MHz are due to free-free absorption of thermal and synchrotron emission (Section 1.3.2) in a cool ($T_e \leq 1000$ K) thermal plasma. However, this kind of cool ionized component of the ISM has not been found to date. Contrary to strongly star-forming galaxies, which are known to show turnovers due to free-free absorption in their spectra (Clemens et al. 2010, Adebahr et al. 2013), it is still under debate if the same effects can also be observed in the normal star-forming galaxies. If free-free absorption is the main agent responsible for the observed spectral turnovers, then flattening of spectra at low frequencies should be correlated with a tilt of galactic disks. Israel & Mahoney (1990) suggested that the postulated free-free absorption was more

significant in the edge-on galaxies, but this was later refuted by Hummel (1991) after extended analysis of the same data. Recently, Marvil et al. (2015), analysed flattenings in the integrated spectra of nearby galaxies, also concluding that there is no dependence on the inclination angle.

Free-free absorption has even stronger effect on radio emission of local regions in galaxies and shape of their radio spectra. The observed local spectra in the centres of galaxies showed that free-free absorption is necessary to account for the spectral turnovers. For instance, the spectrum of Galactic Centre shows a clear turnover at low frequencies (Roy & Pramesh Rao 2006), as well as a remarkable emission from the HII region, Sgr A West, which can be seen as a depression in the radio emission at 332 MHz, while the same object is the brightest region of Sgr Complex at 1400 MHz (Pedlar et al. 1989). Such an effect is also to be seen in the centre of M 82 at 408 MHz (Wills et al. 1997) and 150 MHz (Varenius et al. 2015). A weak flattening in the integrated spectrum of M 82 at frequencies below 300 MHz was explained by free-free absorption (Condon 1992, Yoast-Hull et al. 2013, Lacki 2013, Adebahr et al. 2013). Interestingly, very-low-frequency observations of the Milky Way revealed a spectral turnover at 3 MHz in its global (integrated) spectrum (Brown 1973).

At low frequencies, the CREs energy loss mechanisms, as non-thermal bremsstrahlung and ionization, may become more efficient than the synchrotron and inverse Compton (IC) cooling, which are stronger at higher frequencies (Hummel 1991, Murphy 2009, see also Section 1.4). Also the mechanisms of CREs escape, diffusion or advection (Section 1.5), are also more significant in comparison to synchrotron emission at low frequencies. Thus, the synchrotron radio spectra can be flatter at low frequencies and steeper at high frequencies. Such an argumentation was also proposed by other authors, instead of free-free absorption as an explanation of the observed curved radio spectra. Because of difficulties of obtaining sensitive and high-resolution low-frequency measurements, the discussion of the processes that shape galaxy spectra, therein role of the free-free absorption, still goes on (Marvil et al. 2015, Basu et al. 2015, Mulcahy et al. 2018). Moreover, the synchrotron self-absorption and Razin effect can further reduce the radio emission from regions of dense interstellar medium (ISM) and produce breaks in the integrated spectra of galaxies below 10 MHz (Lacki 2013). Therefore, high-quality low-frequency observations of nearby galaxies at different inclination angle are crucial to assess the importance of free-free absorption. Theoretical approaches, as modelling of radio spectra, are also needed to further investigate free-free absorption, as well as its global and local role in galaxies.

The low-frequency radio continuum emission allows us also to study the low-energy cosmic-rays electrons and energy losses of these relativistic particles. Low-frequency observations enable us to investigate the low-energy population of CREs, which, as less affected by energy losses, are expected to reach out to larger radii from the galactic centre. For galactic outflows, this implies that the magnetized plasma can be traced for a longer time after the termination of the starburst and thus out to larger distances into the halo. There is more evidence that magnetic fields can be transported deep into the intergalactic space (Bernet et al. 2013). Synchrotron emission in such regions located far from the sites of CREs acceleration is rather weak due to low density of CREs, which also undergo energy loss processes. Accordingly, we believe that such observations will be able

to reveal extended disks of face-on galaxies as well as halos of highly inclined galaxies.

The origin of CREs in halos of edge-on galaxies and in the outskirts of face-on galaxies has not yet been resolved. CREs are accelerated in supernova remnants within the star-forming disks of galaxies and they can diffuse out of the disk. The relativistic particles can also be transported in galactic wind flows together with the gas (advection), or accelerated by turbulent processes within such flows. Galactic winds have been observed in starburst galaxies like NGC 253 (Heckman et al. 1990), but not yet in any normal star-forming galaxy. At low frequencies, CREs propagation is more effective, and determining scale heights (for the edge-on galaxies) or scale lengths (for the face-on galaxies) of radio emission, along with similar scales at higher frequencies, could help to settle which propagation mechanism is most plausible in normal star-forming galaxies.

The current scarcity of data at low radio frequencies emphasize the need to explore this regime of the electromagnetic spectrum. The LOFAR (van Haarlem et al. 2013, see also Section 1.7) operating in the mostly unexplored frequency range between 10 and 240 MHz, indeed opened new possibilities to study the diffuse and extended radio continuum emission in halos, free-free absorption in the integrated galactic spectra and in galactic disks, CREs propagations and energy losses, as well as magnetic fields of nearby galaxies. Upcoming new observations and comprehensive modelling of radio spectra will make it possible to address many outstanding questions and shed a new light on the previous often contradicting findings.

1.2 Purpose of the thesis

One of the crucial current astrophysical problems is to fully understand the role of processes to shape the integrated spectra of star-forming galaxies. It is commonly accepted that free-free absorption play an important role in galaxies with a high star-formation rate. Spectral turnovers have been observed in the integrated spectra of M 82 at about 500 MHz (Adebahr et al. 2013) and NGC 253 at 230 MHz (Kapińska et al. 2017). Similar spectral features are also present in the integrated spectra of galaxies known as luminous infrared galaxies (LIRGs) and ultra-luminous infrared galaxies (ULIRGs) (Clemens et al. 2010). However, their spectral turnovers appear at high frequencies of about 1000 MHz (Figure 1.1). Furthermore, the multiple turnovers present in their integrated radio spectra are believed to be caused by free-free absorption of dominant synchrotron sources in the galactic disk (Clemens et al. 2010). Unlike commonly observed turnovers of the integrated radio spectra of galaxies with high star-formation rate, the role of the same effects in nearby star-forming galaxies is still under debate.

The recent low-frequency observations of nearby star-forming galaxies like M 51 and NGC 891 (Mulcahy et al. 2014, 2018), while still scanty, demonstrated that the integrated spectra of these galaxies are not affected by free-free absorption down to the frequency of about 150 MHz. Similarly, the studies of the grand-design spiral galaxy, NGC 6946 at frequencies down to 333 MHz (Basu et al. 2012) also indicated that its integrated spectrum does not reveal any flattening. There arises a key question about the actual role of physical processes such as free-free absorption, CREs propagation and energy losses

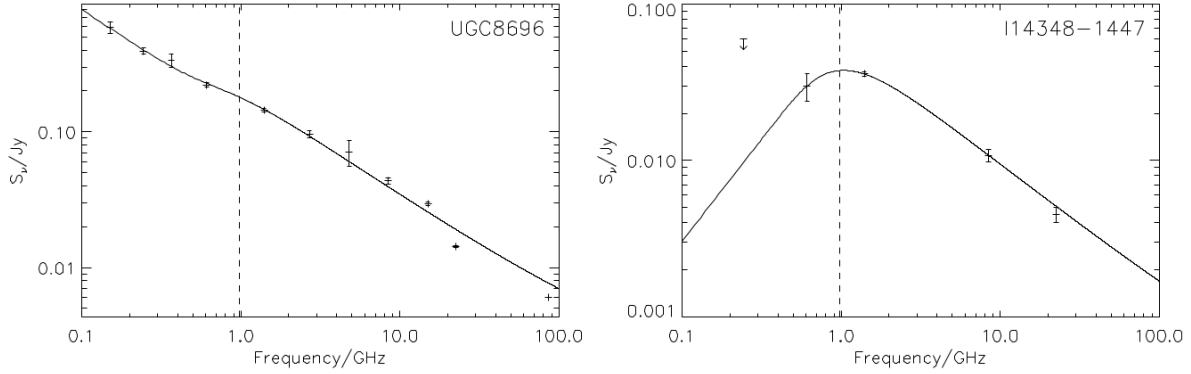


Figure 1.1: The integrated radio spectra of two objects from the (U)LIRGs sample observed by Clemens et al. (2010). The vertical dashed line indicates the location of spectral turnover.

in shaping the galactic spectra.

In this thesis, I aim to investigate properties of low-frequency radio emission of nearby star-forming galaxies, their local and integrated spectra, and the role of free-free absorption. This doctoral thesis is divided into five chapters, followed by five appendixes and bibliography. In Section 1.3 of this Chapter, I present an overview of main radiation processes responsible for radio emission from the normal galaxies. Synchrotron radiation traces the distribution of CREs, which can be affected by different energy losses and modify the shape of synchrotron spectrum as described in Section 1.4. Moreover, CREs can be transported within and out of the galactic disk either by diffusion, or advection in a galactic wind. These two mechanisms of CREs propagation are described in Section 1.5. The nearby star-forming galaxies have been little studied at low frequencies due to technical obstacles and challenges of radio interferometry in this range of frequencies, which are discussed in Section 1.6. Currently, new observational prospects at low radio frequencies become available due to such instruments like the LOFAR. The overview of this novel radio interferometer is provided in Section 1.7, followed by description of the first northern-sky LOFAR imaging survey in Section 1.8.

In Chapter 2, we use for the first time our observations of radio continuum emission of NGC 6946 at 144 MHz observed with the LOFAR High Band Antenna (HBA) Array to shed a new light on free-free absorption, CREs energy losses and their propagation, and galactic magnetic fields at low radio frequencies. In Chapter 3, I introduce a 3D model of radio emission of galaxies and investigate the role of various physical parameters of galaxies as well as projection effects on the integrated galactic spectra. In Chapter 4, I discuss and interpret the spectra of typical nearby star-forming and starburst galaxies basing on thorough modelling of M 51-like galaxies and M 82-like starburst objects. The Chapters 3 and 4 contain an extended discussion of the models and results, which has been already published by Chyży, Jurusik et al. (2018). In the last Chapter 5, the summary as well as prospects for further studies are presented.

1.3 Radio emission from galaxies

1.3.1 Synchrotron radiation

The synchrotron, or non-thermal, emission is produced by relativistic electrons, which were energized in the turbulent ISM or in the intergalactic medium (IGM). It is commonly accepted that CREs are accelerated in shock waves caused by supernova explosions (supernova remnants, SNR) (Condon 1992). In galaxy clusters, shock waves are generated by active galactic nuclei (AGN) and merging galaxies.

The relativistic electrons, each of charge e , with energies $E = \gamma m_e c^2$, where $\gamma = (1 + \beta^2)^{-1/2}$ is the Lorentz factor, $\beta = v/c$, where c is the speed of light, and m_e is the electron mass, moving with a velocity $\vec{v}$ in magnetic field $\vec{B}$ are subject to the Lorentz forces $\vec{F} = \frac{e}{c} \vec{v} \times \vec{B}$, which enforce them to gyrate along lines of magnetic field (in helical paths). The corresponding acceleration makes relativistic electrons emit synchrotron radiation into a cone of half-angle γ^{-1} in the direction of its instantaneous velocity. The synchrotron radiation emitted by relativistic electrons has a form of continuous signal, with a spectrum peaked at some characteristic (critical) frequency given by (Longair 2011):

$$\nu_c = \frac{3e}{4\pi m_e^3 c^5} (B \sin \theta) E^2 \quad (1.1)$$

where θ is the pitch angle between the velocity of electrons and direction of magnetic field. This equation after substituting values of the constants and expressing it in more practical units can be written as:

$$\left(\frac{\nu_c}{\text{GHz}} \right) \approx 1.6 \times 10^{-2} \left(\frac{B \sin \theta}{\mu\text{G}} \right) \left(\frac{E}{\text{GeV}} \right)^2 \quad (1.2)$$

The synchrotron power emitted by each electron is given by:

$$-\frac{dE}{dt} = \frac{2}{3} \frac{e^4}{m_e^4 c^5} (B \sin \theta)^2 E^2 \quad (1.3)$$

An ensemble of relativistic electrons can be described by their energy spectrum as the number of density $N(E) dE$ of electrons with energies between E and $E + dE$. Assuming a homogeneous and isotropic population of relativistic electrons with a power-law energy distribution $N(E) dE = N_0 E^{-p} dE$, the total intensity spectrum observed from an optically thin source (Blumenthal & Gould 1970) varies with frequency as:

$$I_\nu \propto \nu^{-\alpha} \quad (1.4)$$

where α is the spectral index, which is related to the energy distribution of electrons with the index p by $\alpha = (p - 1)/2$. The integration over the entire energy range of electrons gives a synchrotron spectrum, which is approximated by a power-law function with spectral index α (Figure 1.2).

The synchrotron spectrum below frequencies where emitting region becomes optically

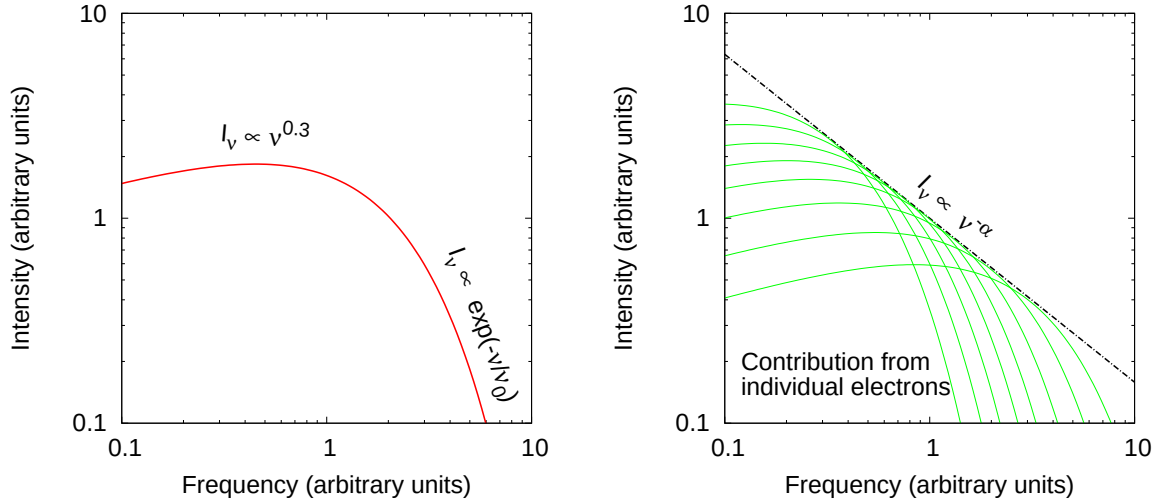


Figure 1.2: (Left) Synchrotron spectrum emitted by a single electron. (Right) Synchrotron spectrum from a population of electrons with a power-law energy distribution (black dot-dashed line). Contributions from individual electrons are represented by green lines.

thick undergoes synchrotron self-absorption and the resulting spectrum is described by:

$$I_\nu \propto \nu^{5/2} \quad (1.5)$$

Synchrotron self-absorption is expected only in sources with brightness temperatures $T_b > m_e c^2 / k \approx 10^{10} \text{ K}$ (Condon 1992). Such high values are actually not observed in normal star-forming galaxies.

Synchrotron radiation emitted by a population of relativistic electrons gyrating in uniform magnetic field is highly linear-polarized. The degree of intrinsic linear polarization is given by:

$$\Pi = \frac{3(p+1)}{3p+7}$$

The theoretical values of Π are quite high, with $p = 2.4$ (i.e. $\alpha = 0.7$) giving the maximum degree of linear polarization of a synchrotron source $\Pi = 72\%$, assuming a uniform magnetic field. Observations show that the degree of linear polarization is generally lower than the theoretical value, since the magnetic field within the source is usually not uniformly distributed, and also due to various depolarization effects (e.g. by telescope beam or Faraday depolarization).

The radio-sky at low frequencies is very bright due to the steep spectrum of synchrotron emission. There is a number of strong sources, such as Cas A, and Cyg A, which have flux densities above 1000 Jy. The low-frequency observations can provide an opportunity to discover new radio sources, which because of sensitivity limits of radio instruments operating at high frequencies have never been observed to date.

1.3.2 Free-free emission and absorption

Inside the star-forming regions, the hydrogen and helium atoms are predominantly ionized and free electrons move on hyperbolic orbits around protons or ionized helium atoms. The

electrons are accelerated (their paths are deviated) by electrostatic attraction of the nuclei. Electron-nucleus interaction results in emission of a photon carrying off the difference of the electron's kinetic energy before and after collision. The radiation emitted in this process is known as free-free emission, thermal emission, or thermal bremsstrahlung (from German *bremsen* = to brake, *Strahlung* = radiation).

The free-free emission emerges from the ionized gas in HII regions and in the diffuse ionized galactic medium (see Appendix B). The classical HII regions are separate clouds of ionized gas (of several parsecs across) surrounding very hot O- and B-type stars. Inside them, there is an equilibrium between ionization and ultraviolet light, and electrons possess thermal velocities with a Maxwellian distribution corresponding to the temperature of plasma ($\approx 10^4$ K).

The emission coefficient of free-free radiation, after Klein et al. (2015), has a form:

$$\epsilon_\nu = \frac{8}{3} \frac{e^6}{c^3} \frac{Z^2}{m_e^2} n_i n_e \cdot \sqrt{\frac{2m_e}{\pi k T_e}} g_{ff} \quad (1.6)$$

where g_{ff} is known as the Gaunt factor ($\ln(p_2/p_1)$), which depends on the lower and upper limits of impact parameters, and n_i , n_e are the number density of ions and electrons, respectively. The atomic number is denoted by Z , T_e is the electron temperature, and k is the Boltzmann constant.

Assuming that the plasma is in the local thermodynamic equilibrium (LTE), from the Kirchhoff's law and the emission coefficient, we can calculate the absorption coefficient $\kappa_\nu = \epsilon_\nu / B_\nu(T)$, where the term $B_\nu(T)$ denotes the black-body radiation described by the Planck function. $B_\nu(T)$ in the regime ($h\nu \ll kT$) is well approximated by the Rayleigh-Jeans law, and the absorption coefficient is given by:

$$\kappa_\nu = \frac{4Z^2 e^6}{3c} \frac{n_i n_e}{\nu^2} \frac{1}{\sqrt{2\pi(m k T)^3}} g_{ff} \quad (1.7)$$

The intensity of radiation arises from a region comprising a medium with known absorption and emission coefficients, and can be calculated from the radiative transfer equation:

$$\frac{dI_\nu}{ds} = \epsilon_\nu - \kappa_\nu I_\nu \quad (1.8)$$

Assuming LTE of plasma with temperature T_e (constant temperature within the source), the solution of the radiative transfer equation for the case of emitting and absorbing gas has a form:

$$\begin{aligned} I_\nu &= \frac{\epsilon_\nu}{\kappa_\nu} (1 - \exp(-\int_0^s \kappa_\nu ds)) = B_\nu(T_e) (1 - \exp(-\tau_\nu)) \\ &= \frac{2kT_e \nu^2}{c^2} (1 - \exp(-\tau_\nu)) \end{aligned} \quad (1.9)$$

where τ_ν is the optical depth given by:

$$\tau_\nu = - \int_0^s \kappa_\nu ds \quad (1.10)$$

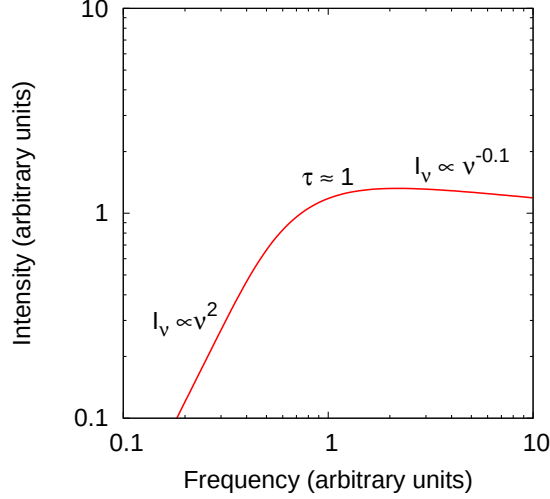


Figure 1.3: Thermal emission from an idealized ionized gas cloud.

Typically, the HII regions are macroscopically neutral with a chemical composition $n_H/n_{He}/n_x$ (x denotes other heavier elements) approximated by the ratio 10/1/0.001, which leads to $n_i \approx n_e$, thus we can assume $n_i n_e = n_e^2$. Then the optical depth of free-free emission can be written as:

$$\tau_\nu = 3.014 \times 10^{-2} \left(\frac{T_e}{\text{K}} \right)^{3/2} \left(\frac{\nu}{\text{GHz}} \right)^2 \left(\frac{EM}{\text{pc cm}^{-6}} \right) < g_{ff} > \quad (1.11)$$

where, $EM = \int n_e^2 ds$ is the emission measure in units pc cm^{-6} , and g_{ff} is the Gaunt factor approximated by (Wilson et al. 2013):

$$g_{ff} = \begin{cases} \ln \left[4.955 \times 10^{-2} \left(\frac{\nu}{\text{GHz}} \right)^{-1} \right] + 1.5 \ln \left(\frac{T_e}{\text{K}} \right) \\ 1 \text{ for } \frac{\nu}{\text{MHz}} \gg \left(\frac{T_e}{\text{K}} \right)^{3/2} \end{cases} \quad (1.12)$$

The Gaunt factor, as given by the upper expression in Equation 1.12, is valid in a wide range of frequencies below 10^3 GHz . A simpler expression for the Gaunt factor is provided by the following approximation $g_{ff} \approx \alpha T^\beta \nu^\gamma$, but it is valid only with additional restrictions for $\nu \leq 20 \text{ GHz}$ and for temperatures $T_e \geq 5000 \text{ K}$ (Altenhoff et al. 1960). Using this simple approximation of g_{ff} , the optical depth can be expressed in the following form:

$$\tau_\nu = 8.235 \times 10^{-2} \left(\frac{T_e}{\text{K}} \right)^{-1.35} \left(\frac{\nu}{\text{GHz}} \right)^{-2.1} \left(\frac{EM}{\text{pc cm}^{-6}} \right) a(\nu, T) \quad (1.13)$$

where the correction factor $a(\nu, T)$ is generally small and equals ≈ 1 .

Using the solution of the radiative transfer equation for the case of uniform plasma in the LTE (Eq. 1.9), the free-free intensity from an optically thin ($\tau_\nu \ll 1$) ionized medium is given by:

$$I_\nu = \frac{2kT_e\nu^2}{c^2} \tau_\nu \propto \nu^{-0.1} \quad (1.14)$$

However, the free-free intensity from an optically thick ($\tau_\nu \gg 1$) ionized gas has a form:

$$I_\nu = \frac{2kT_e \nu^2}{c^2} \propto \nu^2 \quad (1.15)$$

Figure 1.3 presents an example of thermal radio emission for the two above cases: optically thin and thick ionized media. For the frequencies at which thermally emitting plasma is optically opaque, the spectrum has a positive spectral index ($\alpha \approx 2$), while for non-uniform distribution of thermal plasma, the spectrum has a flatter spectral index $\alpha \leq 2$. The spectral index for optically thin thermal emission is typically -0.1 .

Any free electron can gain energy during collision with a nucleus by absorbing a photon, if only the interaction time is sufficient. This process is known as free-free absorption, leads to reducing thermal and synchrotron radiation, especially at low frequencies.

Synchrotron emission with a spectral index α_{nt} observed through an optically thick HII region (a foreground source), can drop off at low frequencies. In such a case, the integrated spectrum has a turnover at frequency, which corresponds to $\tau_\nu \approx 1$ and, as indicated by the solution of the radiative transfer equation, varies with frequency as:

$$I_\nu \propto \nu^{\alpha_{nt}} e^{-\tau_\nu} \quad (1.16)$$

The integrated radio spectra of galaxies involving free-free absorption, are quite often described in the literature by the model of Condon (1992). This 1D analytical model, describing radio emission from a well-mixed uniform synchrotron and thermal gas occupying the given volume, predicts the following behaviour of spectrum:

$$I_\nu \propto \nu^2 (1 - e^{-\tau_\nu}) \left(1 + \frac{1}{f_{th}} \left(\frac{\nu}{\text{GHz}} \right)^{0.1 + \alpha_{nt}} \right) \quad (1.17)$$

where, τ_ν is the free-free optical depth, f_{th} is the thermal fraction at 1 GHz (ratio of the thermal to total emission).

1.4 CREs energy losses and their spectrum

The synchrotron emission observed at radio frequencies traces the underlying distribution of CREs and their energy spectrum. The evolution of energy spectrum of CREs, as they diffuse from their sources through ISM, can be obtained from the diffuse-loss equation (see for more details Appendix A, Eq. A.1). For a continuous electron injection spectrum $Q(E) = \kappa E^{-p}$ and assuming that diffusion is small ($D \approx 0$), the number density of particles per unit energy resulting from the diffuse-loss equation can be expressed as:

$$N(E) = \frac{\kappa E^{-(p-1)}}{(p-1)b(E)} \quad (1.18)$$

where $b(E)$ is the sum of energy-loss processes acting in the ISM:

$$b(E) = - \left(\frac{dE}{dt} \right) = A_1 \left(\ln \left(\frac{E}{m_e c^2} \right) + 19.8 \right) + A_2 E + A_3 E^2 \quad (1.19)$$

The energy losses in the term $b(E)$ are grouped as functions of energy; the term A_1 is weakly dependent on energy and describes the ionization losses. Non-thermal bremsstrahlung and adiabatic losses as proportional to energy are represented by A_2 . The last term A_3 describes the synchrotron and inverse-Compton losses proportional to E^2 . The above energy-loss mechanisms of CREs are described in a more detailed manner in Appendix A.

Actual modification of injected CREs spectrum depends on respective domination of the mentioned energy losses. The following cases are possible:

- $N(E) \propto E^{-(p-1)}$ – domination of ionization losses
- $N(E) \propto E^{-p}$ – domination of non-thermal bremsstrahlung and adiabatic losses
- $N(E) \propto E^{-(p+1)}$ – domination of synchrotron and inverse-Compton losses

Either non-thermal bremsstrahlung or adiabatic losses do not modify the energy spectrum of cosmic-ray electrons, while the other loss processes affect it in twofold ways. The spectrum is flatter by one power of E in the case of ionization losses dominance, and steeper by one power of E if synchrotron and inverse-Compton losses are the most important ones. These results base on the assumption that CREs are injected longer than the time scale of their lifetime. The observed synchrotron spectra ($\propto \nu^{-\alpha_{nt}}$) with the spectral index α_{nt} are directly related to the energy distribution (E^{-p}) with index p via $\alpha = (p-1)/2$ (see Section 1.3.1). Accordingly, the strong ionization losses can lead to flattening of synchrotron spectrum at low frequencies, while synchrotron and inverse-Compton losses steepen the synchrotron spectrum at high frequencies.

It is commonly accepted that CREs in the star-forming galaxies are energized by diffuse shock acceleration (DSA) in SNR shock fronts (of linear size of about 1 pc) of Type II and Ib supernovae. The models of DSA in strong shocks predict the values of α_{nt} at the acceleration site α_{inj} from about 0.5 to about 0.7 (Bell 1978, Biermann & Strom 1993). CREs energy losses and propagation mechanisms (see Section 1.5) lead to synchrotron spectra steeper than the spectra of injected CREs.

The presence of ionized gas (Section 1.3.2) in galaxies complicates further our investigations of the integrated radio spectra of galaxies. Ionized gas in the form of HII regions as well as diffuse ionized gas (DIG, see for more details Appendix B) are sources of free-free radiation with a flat spectrum ($\propto \nu^{-0.1}$). Therefore, the integrated radio spectra are more flat than the synchrotron spectra, since free-free emission contributes most at higher frequencies. What is more, ionized gas can become opaque at low frequencies and through free-free absorption reduce partly synchrotron emission, causing flattening of the integrated radio spectra. More information on ISM, distribution of radio emission, and magnetic fields is presented in Appendix B, C, and D.

1.5 Diffusion and advection of CREs

Cosmic-ray electrons energized in supernova remnants can be then transported through the ISM via either diffusion or advection in a galactic wind. The first process depends on the magnetic field's structure and can account for the highly isotropic distribution of

CREs within galaxies on a macroscopic level. The other process, transport of CREs with gas in a galactic wind flow, has been observed only in starburst galaxies, while diffusion becomes more important in typical star-forming galaxies like the Milky Way (Strong et al. 2011).

Diffusion of CREs and advection in a galactic wind can be distinguished via their CRE propagation length, which depends on the ratio of the transport speed to the radiative time scale of CREs. The transport speed in the case of advection is higher than that of diffusion. Observations of face-on galaxies can be used to determine the scale lengths of radio emission, assuming its exponential distribution as $I_\nu \propto \exp(-r/L)$ (see Appendix C). The scale length L determined from the observations are directly related to the CRE propagation scale lengths and can be used in modelling CREs propagation. For the edge-on galaxies, we can estimate the scale height h , which contains similar information in vertical direction.

In simple diffusion models, the propagation of CREs is described by energy-dependent diffusion coefficient D (Ginzburg et al. 1980). In the solar neighbourhood, the typical values of D derived from fitting diffusion models to direct measurements of cosmic-ray nuclei are around $4 - 6 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (Jones et al. 2001, Moskalenko et al. 2002). Numerical modelling of CREs diffusion in M51 indicated that similar values of D of about $6.6 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$. Slightly higher values of D of about $2 \times 10^{29} \text{ cm}^2 \text{ s}^{-1}$ was reported by Heesen et al. (2009) in the starburst galaxy NGC 253. Using the averaged value of D for a random walk diffusion model, the time scale of CREs is $t_{CRE} = l_{diff}^2/D$ (Murphy 2009), where l_{diff} is the CREs diffusion scale length. Usually, the CREs time scale is dominated by synchrotron losses, and thus, $t_{CRE} = t_{syn} \propto B_{tot}^{-3/2} \nu^{-1/2}$ (see Table A.1 in Appendix A). In a such case, the diffusion scale length depends on the total magnetic field strength and the observation frequency in the following way:

$$l_{diff} \propto B_{tot}^{-3/4} \nu^{-1/4} \quad (1.20)$$

Therefore, we can expect a greater diffusion scale length in galaxies at low radio frequencies, revealing a more extended radio emission than that at high frequencies.

In the starburst galaxies as NGC 253, transport of CREs with gas in galactic wind flow can be analysed basing on estimated values of the bulk speed of CREs. One method to estimate this value was proposed by Heesen et al. (2009), where the bulk speed is defined as a ratio of CREs' exponential scale height h_e and their time scale t_e (for more details of approximation of radio emission in galaxies see Appendix C). The value of h_e can be obtained basing on the synchrotron scale height h_{syn} , derived directly from observations:

$$h_e = \frac{3 + \alpha_{nt}}{2} h_{syn} \quad (1.21)$$

where α_{nt} is the synchrotron spectral index. Assuming that particles lose their energy only through synchrotron radiation, similarly as we assumed for diffusion processes $t_e = t_{syn}$ (see Table A.1). After averaging the values of h_e and calculating the time scales t_{syn} , the lower limit of the bulk speed is given by $v \geq h_e/t_{syn}$. The values of v can be compared with the escape velocity approximated as the maximal velocity of galactic

rotation: $v_{esc} \approx \sqrt{2}v_{max}$. The typical values of v_{max} of 30 km s^{-1} (Wilcots & Miller 1998) lead to the escape velocities of about 40 km s^{-1} . The estimated speed bulk velocity v , considerably larger than v_{esc} , is an indication of galactic wind and advective transport of CREs.

1.6 Challenges of low-frequency observations

While high-resolution ($\approx 1 \text{ arcsec}$), low-frequency ($< 150 \text{ MHz}$) observations are becoming available nowadays, the ionosphere constitutes a major obstacle in exploring of this frequency range. It is a shell of electrons and electrically charged particles and molecules that surrounds the Earth, stretching from a height of about 50 km to more about 1000 km, and distorts radio emission greatly towards low frequencies. The ionosphere shows fluctuations of electron density in a large range of lengths and different scales, which can substantially distort wide-field observations at low frequencies. Historically, its presence limited operation of low-frequency interferometers to short baselines below 3 km, which resulted in poor angular resolution of observation. Due to these fluctuations, different regions of the sky are seen with different properties. This is a source of errors to be found in images, which show artifacts related to the strongest sources far away from the phase centre (off-axis sources). An important step forward has been with the development of calibration technique for using 74 MHz system on the VLA (Cohen et al. 2007), known as self-calibration. However, the self-calibration algorithm cannot simultaneously correct phase errors due to ionospheric density fluctuation. The quality of low-frequency maps can be improved only by applying a technique known as “peeling”, which consists in direction-dependent self-calibration and removing problematic off-axis sources from data (Noordam 2004).

The low-frequency total intensity radio observations are also troublesome due to effects of strong off-axis sources. Such sources, often brighter up to four orders of magnitude than the target, can distort the visibility data by introducing a signal through the sidelobes. These strong radio sources, such as Cas A, Cyg A, Via A, and Tau A, known as “A-Team”, have flux densities in the range of 1000 - 10000 Jy at low frequencies. A successful procedure of removing the influence of strong sources (called demixing) has been developed. Furthermore, the quality of data can be also impacted by solar flares, especially due to interferences over short baselines, which appear as grating rings in the maps. Removing this effect requires manual flagging of data.

Moreover, the radio polarimetry at low frequencies can be affected by a number of other effects. Due to its electric content, the ionosphere can rotate the polarized vectors of the passing radio signal several times, leading to its significant depolarization through the Faraday rotation, which is more important at lower frequencies. In order to reliably estimate the polarization of the source, one needs a model of the ionosphere for removing its contribution. The interstellar medium in the disk of the Milky Way can dominate the observed polarized emission at low frequencies of about 350 MHz, especially while observing the target at low Galactic latitudes. Thus, low-frequency studies of the background radio sources are difficult due to rotation of their intrinsic polarization angle within the



Figure 1.4: Location of the European LOFAR stations: 38 in the Netherlands, 6 in Germany, 3 in Poland, and 1 each in France, England, Sweden, Italy and Ireland. A station in Latvia is planned for 2019. Source: <https://www.astron.nl/lofar-crosses-alps-italy-joins>

source itself, the IGM, the Galactic ISM, and the ionosphere.

1.7 Observations with LOFAR

The low-Frequency Array (LOFAR, van Haarlem et al. 2013) is a novel radio telescope optimized in the mostly unexplored low-frequency range from 10 MHz to 240 MHz. LOFAR consists of a multitude of low-cost antennas, grouped into stations. Each station is equipped with two different kind of dipoles: the Low Band Antenna (LBA), and the Hight Band Antenna (HBA). The LBAs, having shape of inverted-V crossed dipoles oriented in NE-SW and SE-NW, cover the frequency range of 10 - 90 MHz. The HBAs are arranged into tiles of 4×4 array of bowtie-shaped crossed dipoles. The complete configuration of LOFAR has many arrays of stations (core (CS) and remote stations (RS)) distributed over 100 km within the Netherlands and out to more than 1000 km throughout Europe. Currently, also in Poland there are three fully operating international LOFAR stations in Baldy, Borówiec, and Łazy (Figure 1.4). The LOFAR station comprises of 96 LBA antennas, and 48 HBA antennas, while the stations outside the Netherlands have 96 HBA antennas (Figure 1.5). Each station works as a phased array and additional delays are applied to phases of the signal received by the dipoles in order to reinforce the radiation pattern of the array towards the observed target and suppress it in other the directions. Remarkably, the LOFAR can create a beam in more than one direction at the same time and perform simultaneous observations of dozens of targets (limited by the bandwidth which is necessary to send signal to the correlator).

LOFAR offers a different configuration of the LBA and HBA dipoles during observations. There are two commonly used configurations of LBA dipoles: LBA_INNER (active

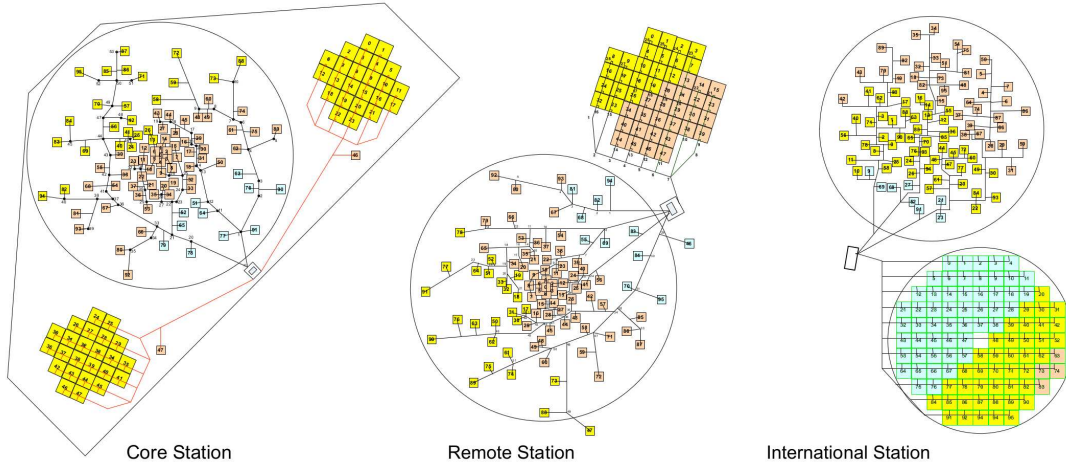


Figure 1.5: Sketch of LOFAR layout of core, remote and international stations. The LBA antennas are within the large circles, whereas the HBA antennas are denoted as small squares.

dipoles only in the inner zone of the station) and LBA_OUTER (active dipoles only in the outer zone of the station). The more concentrated dipoles in the inner zone lead to a lesser effect from the side-lobes and a wider field of view, while the sensitivity is lower. In the case of HBA dipoles in the core stations, they are organized into two different sub-stations, which can be used together or as standalone stations in order to increase the number of available baselines. The second configuration, known as the HBA_DUAL observing mode is also commonly used.

The signals from the LOFAR stations are transferred over large distances using high-speed data links, allowing a transfer of 10 GB/s for each station, to a high-performance supercomputer in Groningen in the Netherlands. Currently, a new correlator is available, named COBALT, which computes cross-correlations between all LOFAR stations (visibilities) with input and output data rates over 50 GB/s. Such a high level of transfer and processing performance is indispensable due to the large volume of data collected by the LOFAR. Typical twelve-hour observational sessions with the LOFAR can require data storage capabilities of about 10 to 100 TB. This can also explain the need of supercomputers to perform data reduction of such immense a volume of data.

LOFAR observations can allow to address a number of still outstanding scientific questions in astronomy. This is reflected by the variety of the Key Science Projects (KSPs) intending to use this instrument for studies of cosmic magnetisms, cosmic-rays, the epoch of re-ionization, space weather, solar physics, sky surveys, and transient sources.

In this thesis LOFAR HBA observations of a nearby galaxy NGC 6946 will be analysed (Chapter 2).

1.8 Multifrequency Snapshot Sky Survey

The Multifrequency Snapshot Sky Survey (MSSS, Heald et al. 2010) is the first LOFAR imaging survey of the northern sky. The primary motivation behind MSSS was to produce an accurate sky model, that could be then used for the purpose of calibrating data from further scientific observations with the LOFAR. However, it can be also used for scientific

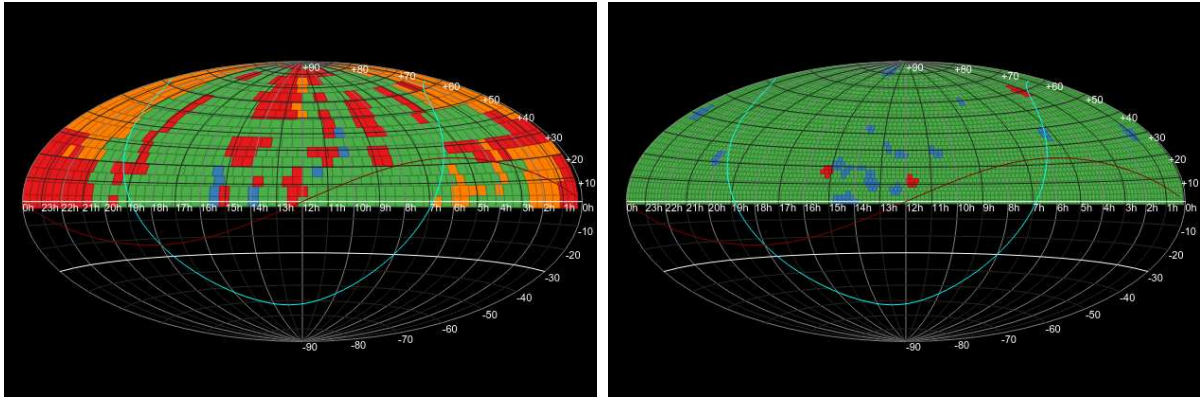


Figure 1.6: Current status of MSSS-LBA (left panel) and MSSS-HBA (right panel) are presented as maps of the all sky. Green regions show fields already observed, violet and blue regions show data under processing. Missing or invalid data are represented by red colour, while fields which have not been observed yet are orange.

research. Based on MSSS survey, we investigated low-frequency spectra of angularly large nearby galaxies (Chyży, Jurusik et al. 2018). The LBA part of MSSS is designed to cover frequencies from 30 to 70 MHz, and the observations are performed using the LBA_INNER configuration, which utilizes the inner 48 dipoles of each 96-dipole stations. The HBA component of MSSS covers a frequency range from 120 to 160 MHz, and the observations are done in HBA_DUAL_INNER mode. In this mode, 24-tile sub-stations of the core stations serve as standalone stations, while for the remote station 24 out of the 48 tiles are disabled.

Table 1.1: LOFAR MSSS overview.

Survey	MSSS-LBA	MSSS-HBA
Station configuration	LBA_INNER	HBA_DUAL_INNER
Field of view per field (FWHM, degrees)	9.77 @ 60 MHz	3.80 @ 150 MHz
Sensitivity (mJy/beam)	< 15	< 5
Angular resolution (arcsec)	< 100	< 120
Bandwidth (MHz) per field	16	16
Number of simultaneous fields	5 (+calibrator)	6
Time per field	9 x 11 min	2 x 7 min
Required number of fields	660	3616
Required on-source observing time (hr)	218	141

Each spectral window of MSSS-LBA and MSSS-HBA has been simultaneously observed in 8 bands of 2 MHz each. The bands' central frequencies for the LBA component of MSSS are 31, 37, 43, 49, 54, 60, 66, and 74 MHz, and for the HBA component: 120, 125, 129, 135, 143, 147, 151, and 157 MHz, respectively. In every MSSS observation the multi-pointing capability is applied to observe six fields at the same time. During the HBA observations, it is not necessary to observe the calibrator, as it was implemented in MSSS-LBA (one of six field contained a standard calibrator) ensuring a much better stability. During the MSSS observations, besides all the Dutch stations also the international station are included. However currently available data products results from the initial processing, and are limited to the core and inner remote stations for MSSS-HBA, and 10-km baselines for MSSS-LBA component. The basic parameters of the MSSS survey

are provided in Table 1.1. The current status of MSSS observations is presented in Figure 1.6.

CHAPTER 2

LOFAR HBA observations of NGC 6946

2.1 Introduction

NGC 6946, discovered by German-British astronomer William Herschel on 9 September 1798 is located in the sky at the boundary of the northern constellations of Cepheus and Cygnus. The galaxy is also known as “Fireworks Galaxy” or “Pyrobolus Cygni” due to the record number of supernovae observed in it (about nine supernovae within the past 100 years). NGC 6946 belongs to the group of seven more massive nearby galaxies in the Local Volume (LV) within a distance of 7 Mpc. Roughly a half of the population of the LV are within the reach of gravitational influence of those giant 7 galaxies (Karachentsev et al. 1999). Interestingly enough, all of these “oligarchs”, except for NGC 6946, have a lot of dwarf companions. The absence of dwarf systems around this galaxy within radius of 1 Mpc constitutes a remarkable anomaly. Visibility of potential faint dwarf companions of NGC 6946 is strongly affected by substantial Galactic extinction resulting from the low galactic latitude ($b = 12$ deg.) of this galaxy. On the other hand, apparent lack of nearby dwarf galaxies in neighbourhood of NGC 6946 can be related to its location at the border of the Local Void (Tully 1988). For a long time, NGC 6946 seemed to be an isolated system, until a discovery of a group of galaxies surrounding it (Karachentsev et al. 2000). Among a dozen of these objects at least 7 are dwarf irregular galaxies gravitationally bounded to NGC 6946.

Proximity of NGC 6946 and its large optical extent (more than $12'$) along with its low inclination (38 degrees) make this galaxy an ideal object for studies of density waves, spatially resolved star formation activity, and various processes acting in the ISM, as CREs and magnetic fields generation and evolution. The physical parameters of NGC 6946 assumed in this chapter are given in Table 2.1. In the optical band the galaxy can be seen as a classical grand-design spiral galaxy with multiple spiral arms and a small bright nucleus (Figure 2.1, left panel). Among the six spiral arms that emerge from galaxy centre (Tacconi & Young 1990), three arms in the north-east part are well-defined, while the remaining arms, in the south-western quadrant, are less developed. Lack of prominent dust lanes at inner edges of spiral arms can indicate relatively weak density waves. NGC 6946 is a moderately active star-forming galaxy having a global star-formation rate of about $7.1 M_{\odot} \text{yr}^{-1}$ (Kennicutt et al. 2011). There is no strong evidence for AGN activity at the nucleus (Tsai et al. 2006), and the apparent star-formation from the centre is rather mild

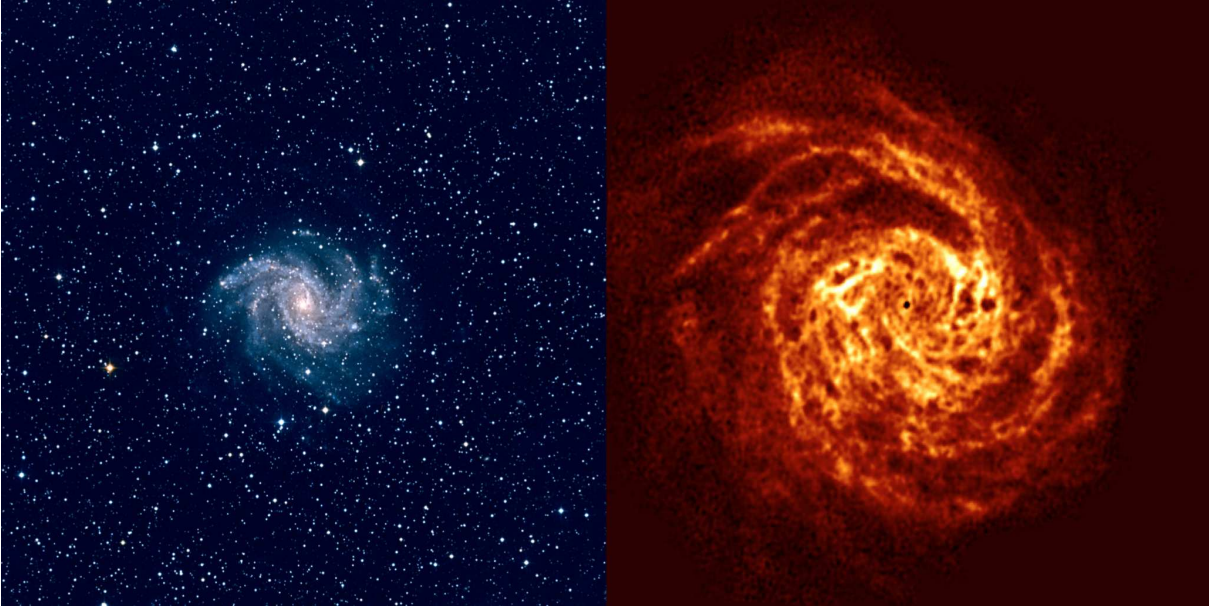


Figure 2.1: (Left) Optical colour image made from the Digitized Sky Survey plates. (Right) The deep HI map on the same scale as the optical image on the left. Both the panels are from Boomsma et al. (2008).

Table 2.1: Observational parameters of NGC 6946.

Type ^a	SAB(rs)cd
Position of nucleus ^b (J2000)	RA=20 ^h 34 ^m 52.3 ^s DEC=60°09′14″
Position angle ^c	242°
Inclination ^c	38°
Distance ^d	6.8 Mpc
D_{25} ^e	11.2′
Conversion 1′	1.75 kpc

References: ^a de Vaucouleurs et al. (1976); ^b van Dyk et al. (1994); ^c Boomsma et al. (2008); ^d Karachentsev et al. (2000); ^e Carignan et al. (1990);

(Ball et al. 1985).

In many spiral galaxies the HI disk is much more extended than the optical emission. In NGC 6946 the emission from neutral hydrogen seen in Figure 2.1 (right panel) from inner part of disk follows closely the optical spiral-arm pattern. The morphology of spiral galaxies, especially that at 21 cm emission line, can provide information about a galaxy’s history, its environment and gravitational interactions. Thus, the quite regular HI disk of NGC 6946 suggests there was no recent and violent interactions with other galaxies.

“Fireworks Galaxy”, one of the largest galaxy in the sky, has been extensively observed at radio frequencies throughout the past few decades. The first radio continuum map available in the literature was obtained as a part of HI observation with the twin-element interferometer of the Owens Valley Radio Observatory (Rogstad et al. 1973). Due to low angular resolution of those initial observations (about 2′), the map showed only an unresolved radio emission from the nucleus and another second peak west to the centre

from the group of HII regions. Early interferometric radio continuum observations at 0.6, 1.4, and 5 GHz with the Westerbork Synthesis Radio Telescope (WSRT) revealed the radio bright disk of NGC 6946, well approximated by an exponential decrease of brightness with radius (van der Kruit et al. 1977). Moreover, a number of discrete sources seen on the map at 5 GHz were mostly identified as groups of HII regions. Later, Klein et al. (1982) observed NGC 6946 at higher frequency of 10.7 GHz with the Effelsberg 100-m radiotelescope and estimated that no more than 30% of the total emission was of thermal origin. Due to separation of the thermal component, the authors argued that the length scale of synchrotron emission is greater than that of thermal one. This could suggest a significant radial diffusion of CREs from star-forming regions in this galaxy.

The radio continuum emission observed at 18.0 and 20.5 cm with the VLA revealed a dominant synchrotron smooth disk with weak signatures of spiral arms (Beck et al. 1991). No asymmetry of optical emission between the north-east and south-west part of galaxy was noticed at 18.0 and 20.5 cm. However, Ehle & Beck (1993), while observing NGC 6946 with the Effelsberg 100-m telescope equipped with a newer receiver at 10.5 GHz, detected radio continuum far beyond optical emission, reaching the same extent as at 18.0 and 20.5 cm (Beck et al. 1991). Interestingly enough, the contrast of radio emission between regions in the arms and in the interarm regions is about 1.2, similar to the contrast at lower frequency of 1.4 GHz (Beck et al. 1991). The radio telescope beam was smaller than the typical separation of spiral arms in NGC 6946, thus the results are only slightly affected by limited angular resolution of observations. Therefore, the observed radio emission is smooth on scales larger than the angular resolution and may be an effect of diffusion of CREs. A more recent map at 20.5 cm, constructed from combined VLA and Effelsberg data (Beck 2007) with better angular resolution of $15''$ (Figure 2.2, left panel), showed an envelope of weak radio emission surrounding NGC 6946, indicating that CREs and magnetic fields are effectively transported beyond the optical arms into intergalactic space.

One of the most remarkable features of NGC 6946 was spotted while investigating polarized radio emission and magnetic fields of the galaxy. Radio-polarized observations at 6 cm (Beck 2007) led to discovering a new phenomenon in galaxies, symmetric magnetic structures between optical spiral arms (“magnetic spiral arms”). Polarized synchrotron emission of NGC 6946, shown in Figure 2.2 (right panel), revealed two such symmetric magnetic spiral arms located almost precisely between the optical spiral arms traced by $H\alpha$ emission. Moreover, not only symmetry of these magnetic features is striking, but also the almost perfect alignment of the observed magnetic field vectors, which are parallel to the optical spiral arms. Several authors (e.g. Moss 1998, Shukurov 1998) proposed magnetohydrodynamical (MHD) dynamo models, which can account for generation of magnetic spiral arms in galaxies. Faraday rotation measure values in NGC 6946, positive in the northern magnetic arm and negative in the southern arm, suggest presence of a coherently directed magnetic field, which can suggest a large-scale dynamo at work within. Alternative mechanisms have been proposed as well, and one of possibilities are slow MHD density waves in the rigidly rotating inner part of a galaxy (e.g. Lou et al. 1999, Poedts & Rogava 2002). Drifting of magnetic field to inter-arm regions in a non-axisymmetric gas flow triggered by a spiral perturbation

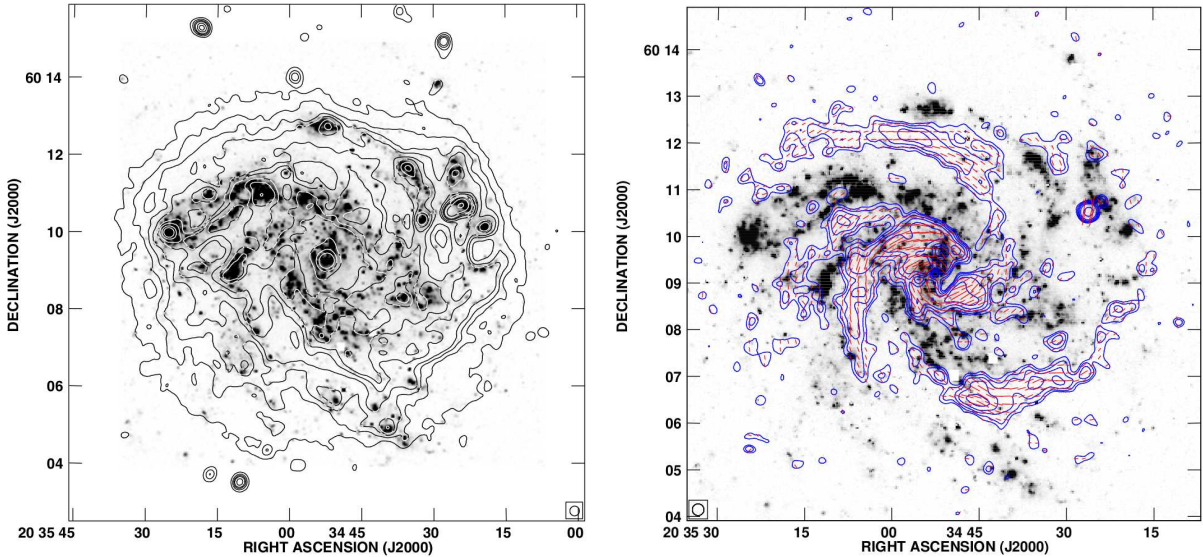


Figure 2.2: (Left) Total intensity map of NGC 6946 shown as contours at 20.5 cm with angular resolution of $15''$ overlaid upon the $H\alpha$ image. The contour levels are $(1, 2, 3, 4, 6, 8, 12, 16, 32, 64, 128) \times 200 \mu\text{Jy}/\text{beam area}$. (Right) Polarized intensity map of NGC 6946 shown as contours (blue lines) and B-vectors (red) at 6 cm overlaid upon the $H\alpha$ image. The angular resolution of map is $15''$. Both the panels are from Beck (2007).

(Otmianowska-Mazur et al. 2002) or by a bar (Kulpa-Dybeł et al. 2011) are also possible, as well as a combination of physical processes like dynamo action, density waves and shearing of flows in NGC 6946.

NGC 6946 has been extensively studied in a wide range of radio frequencies, but only scarcely at frequencies below 500 MHz, mainly due to the technical challenges of radio observations at low frequencies. The galaxy was observed at 57.5 MHz as a part of a survey of 133 spiral galaxies (Israel & Mahoney 1990). Low angular resolution observations enabled only to measure the total flux density of $13 \pm 2 \text{ Jy}$, which was lower than the extrapolated high frequency flux density assuming a constant spectral index. Despite the flux measurements might suffer from uncertainties, the free-free absorption was proposed to account for systematically lower values of flux densities within a sample of galaxies at this frequency (see Section 1.1). At low radio frequencies, we can observe synchrotron emission produced by aged and low-energy cosmic-ray electrons (Section 1.5). The low-energy CREs are less affected by energy losses and can travel into a more distant regions from their site of origin than those at higher frequencies. Therefore, we can expect that spiral galaxies possess extensive radio synchrotron halos to be seen only at low frequencies. Gravitational interaction with physical companions might trigger a more significant ejection of magnetized plasma into intergalactic medium than in non-interacting objects. Thus, low-energy cosmic-ray electrons can illuminate rarefied magnetic structures, not visible at higher frequencies.

NGC 6946 was also observed at frequencies below 500 MHz as a part of the small survey of six galaxies at 333 MHz by Basu et al. (2012) with the Giant Meterwave Radio Telescope (GMRT). The integrated flux density of this galaxy at 333 MHz is consistent with other flux densities at higher frequencies, and there is no indication of spectral flattening of the integrated spectrum towards this frequency. Radio emission of all six

observed galaxies, including NGC 6946, is apparently more smooth and spiral arms are often less defined than at higher frequencies. The authors proposed preliminarily, that the observed radio emission comes from a population of old CREs ($> 10^7$ yrs), that diffused away from their origin sites, filling up volume of a radius of about 1 kpc. Thus, CREs without losing much of their energy could reach larger distances than the typical width of gaseous spiral arms. Due to the fact that data below 300 MHz of radio emission of galaxies are still scarce, our knowledge of low-energy population of CREs is very limited. Therefore, low-frequency observations of nearby galaxies are of great importance and will lead to better understanding of low-energy CREs physics.

The main scientific aspects of this chapter are supposed to shed a new light on free-free absorption, CREs energy losses and their propagation, and magnetic fields at low radio frequencies. For this purpose, I use for the first time the radio emission of NGC 6946 at 144 MHz observed with the LOFAR HBA Array, which is described in Section 2.2. I aim to use the LOFAR HBA image at central frequency 144 MHz (Section 2.3) to detect any more extended emission by low-energy CREs, than found at higher frequencies. As currently known, there is no flattening of the integrated spectrum of NGC 6946 towards 333 MHz. By deriving such a spectrum using flux density at 144 MHz, I attempt to understand the role of free-free absorption below 300 MHz in the galaxy (Section 2.4.1). I would like also explain the role of free-free absorption at local scales by probing curvature of the local spectrum from the galaxy nucleus (Section 2.4.2). The separation of the thermal emission from the observed radio continuum emission at 144 MHz (Section 2.4.3) allows me to investigate total and synchrotron spectral index maps between 144 and 1400 MHz (Sections 2.4.4). In Section 2.5, I analyse for the first time the radial profile of synchrotron radio emission of NGC 6946 at 144 MHz and radial profile of spectral indexes. I also use synchrotron radio emission at 144 MHz to estimate the total magnetic field strengths within NGC 6946 (Section 2.6). Finally, I discuss the obtained results in Section 2.7 and present my conclusions in Section 2.8.

2.2 Observations and data reduction

We proposed observations of NGC 6946 for the first scientific Cycle 0 of the LOFAR after the instrument commissioning phase (project number: LC0-043). The observations were performed in HBA_DUAL_INNER mode (see Section 1.7) with all the available Dutch LOFAR HBA stations (48 core stations and 13 remote stations). Since there was no need for sub-arcsec resolution, the international stations were not involved. The on-off mode was applied to observe the primary calibrator 3C380 in 1 minute scans interleaved with 12 minute scans of the target source. The total available bandwidth in the used 8-bit mode of the LOFAR was about 95 MHz, splitted into 488 subbands (SBs), each with a bandwidth of 0.195 MHz. The individual subbands consist also of 64 channels, each of about 3 kHz. During the observations the data were recorded within a smaller frequency range of 115 - 178 MHz (324 subbands) to avoid strong Radio Frequency Interference (RFI) usually observed at higher frequency subbands (Offringa et al. 2013). The details of the observations of NGC 6946 are provided in Table 2.2.

We performed data reduction using the LOFAR software from the Standard Imaging Pipeline (hereafter LOFAR SIP: Heald et al. 2010, van Haarlem et al. 2013) and the Common Astronomy Software Applications (CASA) package¹. We found the best strategy of data reduction by working first on one subband of the target and calibrator, and then using the results to set up parameters of the pipeline for the remaining data.

The most computing-intensive steps of the performed LOFAR data reduction are as follows:

- Pre-processing including data flagging (marking data samples as bad), removal of effect of bright sources entered through the sidelobes (demixing), and data compression in time and frequency (averaging).
- Data Calibration including transfer of amplitude gain solutions to a target and phase calibration.
- Imaging of the calibrated data into a map of the sky brightness (deconvolution process).

2.2.1 Pre-processing

We carried out three stages of pre-processing: flagging, demixing and averaging of data, using the New Default Pre-Processing Pipeline (NDPPP), which is the tool from the LOFAR SIP that provides possibility to use great variety of parameters (e.g. thresholds, averaging steps). Flagging was done either by baseline or station identified as bad or using an algorithm called AOFlagger (Offringa et al. 2012) from the NDPPP, with parameters adjusted to our data. The algorithm identifies high amplitude outliers in the time and frequency planes. We set up parameters of AOFlagger to obtain possibly best removal of RFI, and then flagging was applied to all linear correlations (XX, YY, XY, YX) of the raw data of 3C 380 and NGC 6946.

It can be the case that the brightest sources in the sky, known as A-Team sources (e.g. Cas A, Cyg A, Tau A, Vir A), even located outside of intended field of view, are picked up by LOFAR stations, that have some sensitivity in their direction. These sources, often brighter up to four orders of magnitude than the target, are able to distort the

Table 2.2: Details of LOFAR HBA observations of NGC6946.

Phase center N6946 (J2000)	α 20 ^h 34 ^m 52.324 ^s δ +60°09′14.09″
Phase center 3C380 (J2000)	α 18 ^h 29 ^m 31.78 ^s δ +48°44′46.16″
Obs. start	15-Jul-2013/20:02:06.0 (UTC)
Obs. end	16-Jul-2013/03:58:55.0 (UTC)
Scan length on calibrator	1 min
Scan length on target	12 min
Freq. range	115 - 178 MHz
correlator integration time	2s
No of channels per subband	64

¹<http://casa.nrao.edu>

visibility data by entering signal through the sidelobes. We performed simulations of potential contribution from A-Team sources by NDPPP program, applying the procedure of removing the effects of strong sources (called demixing) for Cas A and Cyg A. Their influences were removed by first solving for the station sensitivity in the direction of Cas A and Cyg A, then predicting the contribution to data, and subtracting it.

Averaging of data was performed both in time and frequency. This step enabled compression of data from 64 to 8 channels per subband and from 2 to 12 seconds in time step, thus reducing significantly the amount of data from 14.2 TB to about 1 TB.

2.2.2 Initial calibration

Data of the primary calibrator 3C 380 after pre-processing steps were calibrated with the Black Board Self-cal (BBS) software (Pandey et al. 2009), using the sky model of 3C 380 from Scaife & Heald (2012). Calibration was done by solving for parameters (gains represented as a series of 2×2 complex matrices) that can convert a model of the sky brightness distribution to the measured values. After obtaining the gain solutions for each calibrator subband with the BBS, the gain amplitude solution per station were interpolated in time and transferred to the corresponding subbands of the target. In the next step, we inspected NGC 6946 data after amplitude solution transfer and removed RFI with the NDPPP program. The target data containing 324 SBs were divided into 12 blocks, each consisting of 27 subbands. The subbands within each block were combined in frequency in order to improve the signal to noise ratio. Then, the blocks were phase-calibrated in the BBS using the LOFAR global sky model (GSM). The GSM model is based on the positions of sources from the NRAO VLA Sky Survey (NVSS) catalogue (Condon et al. 1998) and flux densities extrapolated from the power-law fit to data from the VLA Low Frequency Sky Survey (VLSS, Cohen et al. 2007), the Westerbork Northern Sky Survey (WENSS, Rengelink et al. 1997), and the NVSS. Having completed initial calibration, we inspected the results for any RFI or bad solutions, which were then flagged with the NDPPP program.

2.2.3 Imaging and self-calibration

All 12 data blocks after initial amplitude and phase calibration were used to create a new sky model from the deconvoluted images produced with the CASA package and the AWimager (Tasse et al. 2013) from the LOFAR SIP. The data calibrated in BBS can be corrected for one direction only, so the multiplicative direction-dependent effects are present in the image plane. AWimager utilises the A-projection algorithm (Bhatnagar et al. 2008) allowing to produce image corrected for the direction-dependent effects resulting from the primary beam changes in time, and from phase errors due to the ionosphere. Accordingly, such a map includes more accurate positions and flux densities of sources located away from the phase centre and was used in making a new sky model for all the sources except NGC 6946. Subsequently, we created another map of NGC 6946 field with CASA, since multi-frequency and multi-scale cleaning involving w-projections gave better results in imaging of diffuse emission, while those features were not available with the AWimager.

The second map was used in creating a sky model of radio emission of NGC 6946 with all the other sources disregarded. Hence, the initial model for first iteration of self-calibration was a combination of the models for NGC 6946 and the other sources. It was used for phase-only self-calibration with the BBS program, performed for each block of data separately. Next, we inspected the calibrated data of all 12 blocks for RFI, flagging the outliers. The full process of self-calibration was completed after the third iteration. The models for each self-calibration iteration were created using the same procedure.

2.3 Distribution of total radio emission at 144 MHz

The final image of NGC 6946 was obtained from all 12 blocks of data by applying multi-frequency and multi-scale cleaning with w-projections in CASA. We got the best results when Briggs weighting and UV-distance limited to $5k\lambda$ were used.

CASA does not provide any functionality for the primary beam correction of the LOFAR instrument. However, the extent of the LOFAR primary beam is about 3.8° at 144 MHz, much much bigger than the size of NGC 6946, hence any potential flux density errors due to lack of the correction are insignificant. Figure 2.3 shows the emission around NGC 6946 from the map with the angular resolution of $40''$. Small phase errors can be noticed around a number of brighter point sources in the field, since only direction-independent calibration has been applied. However, in the phase centre of the map, near the location of NGC 6946, there are no evident phase errors, due to absence of strong background sources. Both astrometry of several point sources and comparison with the point spread function have not revealed any significant deviations of position or broadening of point sources due to phase errors caused by the ionosphere.

Typical root mean square (rms) noise is approximately $1.5 - 2 \text{ mJy/beam}$ close to NGC 6946, and 0.5 mJy/beam in the quiet regions further away. The theoretical value of thermal noise estimated for our LOFAR observations of NGC 6946 is about $60 \mu\text{Jy/beam}$, image weighting can increase this value by a factor up to 2. Including image weighting the obtained rms noise in the quiet regions is about 4 times greater than the expected thermal noise.

The contour map of the total radio intensity at 144 MHz overlaid onto the optical blue image from the Digitized Sky Survey² is shown in Figure 2.4. An envelope around smooth bright disk of radio emission can be seen far beyond the optical disk. No spiral arms can be clearly discerned on the map with angular resolution of $40''$, however one can notice enhancements of radio emission slightly elongated in the direction of spiral arms and/or HII complexes. The bright nucleus (with a peak flux of 280 mJy/beam) is surrounded by emission resembling a some rectangle with twisted borders. The emission from this inner, bright part of NGC 6946 is comparable to the early low-resolution observations at 0.61 and 1.4 GHz (van der Kruit et al. 1977).

²<http://archive.eso.org/dss/dss>

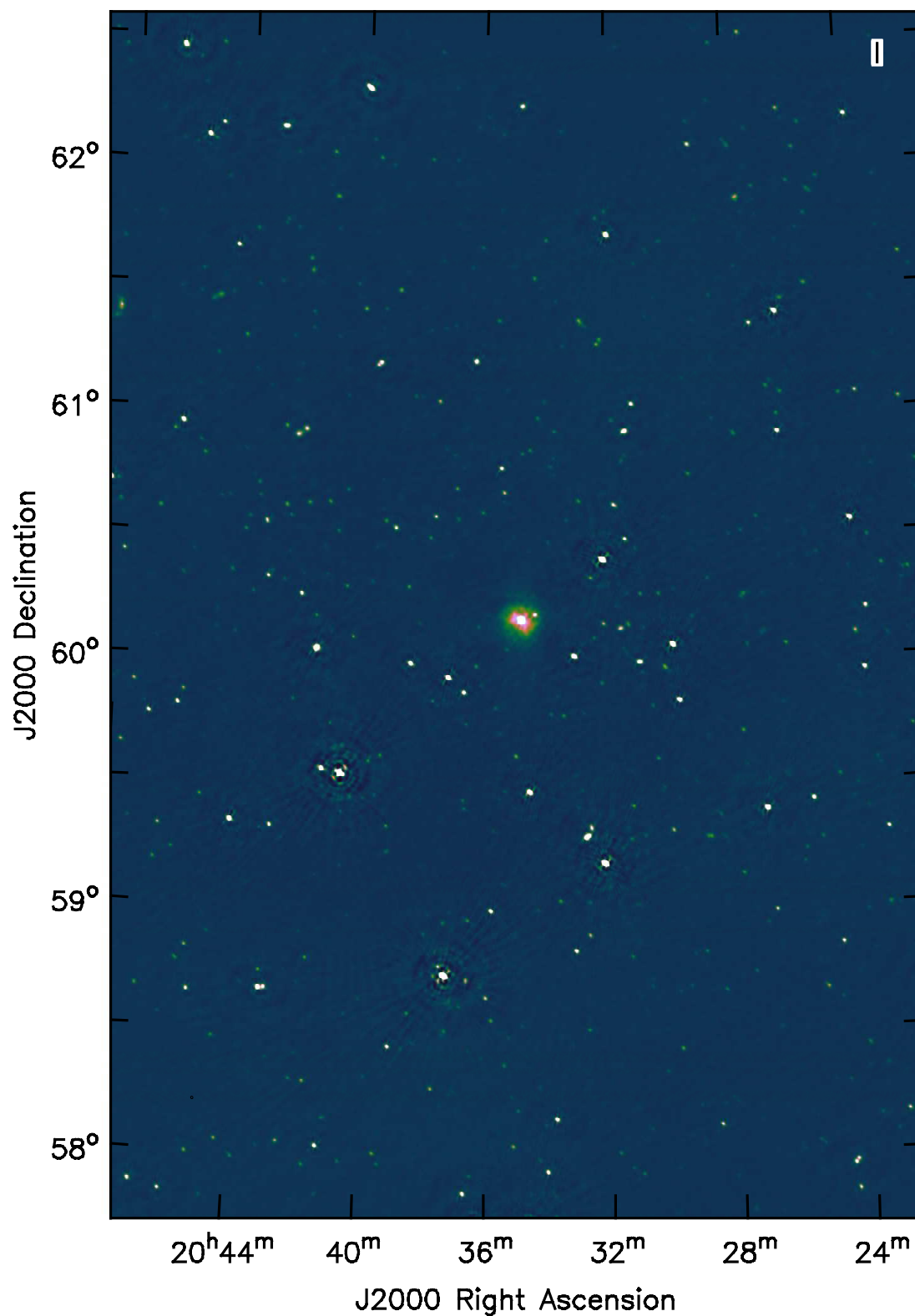


Figure 2.3: Image of field of view around NGC 6946 of LOFAR observations at central frequency of 144 MHz. The map angular resolution is $40''$.

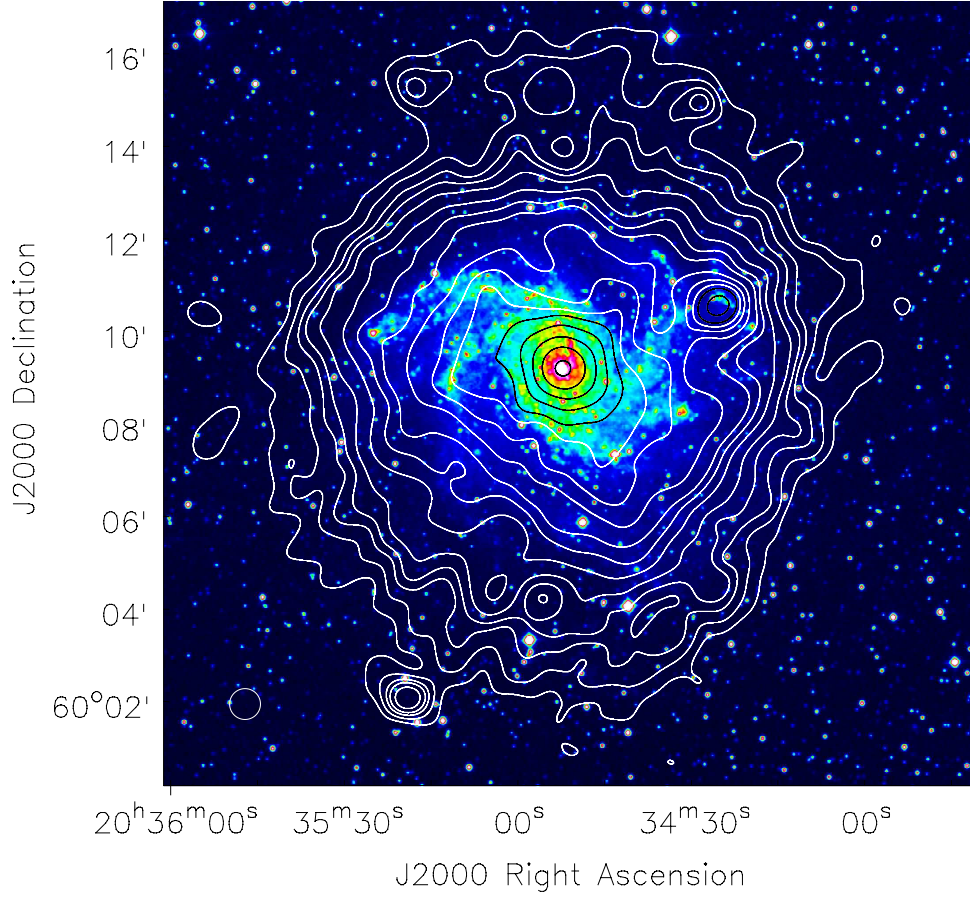


Figure 2.4: LOFAR map of NGC 6946 at central frequency of 144 MHz (contours) at a resolution of $40''$ overlaid onto an optical blue image from the Digitized Sky Survey. The contour levels are $(1, 1.5, 2, 2.4, 3, 4, 5, 6, 8, 10, 12, 14, 18, 24, 32, 44) \times 6$ mJy/beam.

2.4 Spectral properties

2.4.1 Integrated total and synchrotron radio spectrum

Integrated radio spectrum contains information about a source’s physical properties, radiation, and absorption processes from the entire galaxy. The shape of the integrated spectrum is determined by the contribution from synchrotron and free-free (thermal) emissions (see Section 1.3.1 and 1.3.2). The galactic spectra are typically modelled as a sum of the positive power-law $S(\nu) \propto \nu^\alpha$, parametrized by the spectral index α for the synchrotron and thermal emission, respectively. The overall emission from those two types of radiation gives a rise to a power-law spectrum with spectral index α , which is flatter than the synchrotron spectrum with α_{nt} . Moreover, different CREs energy losses can modify the shape of synchrotron spectrum (Appendix A). Significant synchrotron and IC losses may lead to steepening of synchrotron spectrum, as observed at higher frequencies. However, due to presence of thermal emission, interpretation of such steepening is usually difficult and requires separation of the thermal component. Furthermore, because of scarcity of low-frequency observations of galaxies, the role of ionization losses and free-free absorption, which can flatten synchrotron spectrum at low radio frequencies,

is still not too well understood.

The previous multi-frequency radio observations of NGC 6946 revealed that there is no clear flattening of the integrated radio spectrum of the galaxy down to 333 MHz (Basu et al. 2012) due to free-free absorption or ionization losses. We constructed the integrated radio spectrum of NGC 6946 using flux measurement at 144 MHz from our LOFAR observations to investigate potential flattening of the spectrum below 333 MHz.

The flux density at 144 MHz was estimated by integration of radio emission (Figure 2.3) in concentric rings formed by minor and major axis, considering the projection of the NGC 6946 on the sky. Before making this step, we removed from the map at 144 MHz background point sources by subtracting fitted Gaussian component. The flux density obtained from integration out to a radius of 18 kpc is 8.7 ± 0.6 Jy.

In order to construct an integrated radio spectrum with LOFAR data, we searched the literature on NGC 6946 and found the available values of flux density, summarised in Table 2.3. The flux densities are provided in their original flux scales, the LOFAR flux density is in the RCB scale (Roger et al. 1973). At low radio frequencies most of data are in the KPW scale (Kellerman et al. 1963), which is in agreement with the RCB scale at frequencies above 325 MHz. Most of high-frequency data are in the B77 scale (Baars et al. 1977), which is not recommended due to decrease in the flux density of Cas A at low frequencies. We estimated that the correction factors to the RCB scale in our case are small, leading to corrections comparable to flux density uncertainties (usually less than 10%, see also Scaife & Heald 2012), thus, the correction was not applied. Flux density at 57.5 MHz (Israel & Mahoney 1990) might be systematically underestimated as for the whole survey the ratio of diameter of radio emission to optical diameter has the mean value of 0.8, which means radio detection from only the inner part of the galaxy with strong star formation. The flux density at 38 MHz (Hales et al. 1995) is a catalogue value (a single-component source) from a radio survey carried out with the Cambridge Low-Frequency Synthesis Telescope (CLFST). Both the measurements at 38 MHz and 57.5 MHz come from low-frequency interferometers and due to missing short spacings, the detection of diffuse emission from NGC 6946 was not possible, thus the measured flux densities are underestimated. Consequently, the literature measurements below the LOFAR HBA data have not taken into account in further analysis of integrated radio spectrum.

In order to study the synchrotron spectrum of NGC 6946, we subtracted the thermal emission at all frequencies using the integrated thermal flux density of 97 ± 13 mJy at 1400 MHz from Tabatabaei et al. (2013). Assuming that thermal emission arises solely from the optically thin regions, we calculated thermal flux densities at different frequencies using the thermal spectral index of -0.1 . The thermal flux density at 1400 MHz corresponds to the thermal fraction of 6.7 ± 1.3 %, which agrees well with the values of thermal fractions calculated basing on the sample of spiral galaxies as 8 ± 1 % by Niklas et al. (1997b) and 9 ± 3 % by Marvil et al. (2015). The calculated value of thermal fraction at 144 MHz is lower than at 1400 MHz and equals 1.4%. The spectrum of integrated total synchrotron flux density is shown in Figure 2.5.

The synchrotron spectrum (Figure 2.5, left panel) was first analysed using a single power-law (SPL) model $S \propto \nu^{\alpha_{nt}}$. We used the Marquard-Levenberg algorithm to find

Table 2.3: Integrated flux density of NGC 6946 from literature.

Frequency GHz	Flux density Jy	Error Jy	Reference
0.038	12.9	1.29	Hales et al. (1995)
0.057	13.0	2.00	Israel & Mahoney (1990)
0.144	8.70	0.60	this work
0.158	7.54	3.54	Brown & Hazard (1961)
0.178	5.88	0.44	Caswell & Wills (1967)
0.333	4.50	0.24	Basu et al. (2012)
0.408	3.95	0.40	Gioia & Gregorini (1980)
0.610	2.80	0.20	van der Kruit et al. (1977)
1.415	1.50	0.10	van der Kruit et al. (1977)
1.465	1.41	0.08	Basu et al. (2012)
4.85	0.63	0.05	Klein et al. (1982)
4.86	0.54	0.05	Basu et al. (2012)
8.50	0.45	0.05	Kuril'chik et al. (1970)
10.55	0.39	0.02	Ehle & Beck (1993)
10.77	0.36	0.04	Klein et al. (1982)

the spectral index $\alpha_{nt} = -0.79 \pm 0.05$, which gave the lowest reduced chi-square parameter $\chi_{red}^2 = 0.137$. Figure 2.5 (left panel) depicts the best fit of SPL model shown as red solid line. The power-law model of synchrotron spectrum after adding thermal spectrum was used to reconstruct the expected total radio spectrum, presented as red solid line in the right panel in Figure 2.5. The thermal spectrum is shown as green dotted line in Figure 2.5 (left panel). This model, containing both the thermal and synchrotron emissions has a reduced $\chi_{red}^2 = 0.131$.

Any curvature in the synchrotron spectrum can be investigated by applying an empirical model with a second-order polynomial of the form $\log S(\nu) = \log a_0 + a_1 \log \nu + a_2 (\log \nu)^2$, where, a_1 is the spectral index and a_2 is the curvature parameter. The best fitted model was obtained for the following values of parameters: $a_1 = -0.76 \pm 0.09$ and $a_2 = 0.038 \pm 0.10$. The model has a reduced $\chi_{red}^2 = 0.148$ and is shown as an orange dashed line in Figure 2.5 (left panel). As before, we added the thermal spectrum to the polynomial model of synchrotron spectrum to obtain the expected integrated spectrum (orange dashed line in the right panel of Figure 2.5). A reduced value of χ_{red}^2 for the fit of the model of total spectrum to the integrated spectrum equals 0.137 and is higher than than for a similar model of integrated spectrum involving the power-law synchrotron component. This result suggests that the synchrotron spectrum is well reproduced by a simple power-law.

Towards 144 MHz, there is no indication that the integrated spectrum of NGC 6946 flattens due to free-free absorption or ionization losses. The potential flattening towards lower frequencies with the spectral index between 57.5 and 144 MHz $\alpha = -0.43 \pm 0.01$ is uncertain, since available flux density measurements below 144 MHz are not too reliable. Differently than for many starburst galaxies, the shape of the integrated spectrum of NGC 6946 at low frequencies does not deviate from a simple power-law approximation. Therefore, new LOFAR observations in LBA band at about 50 MHz are crucial to verify behaviour of integrated spectrum at low frequencies. In addition to further observations at low frequencies, a comprehensive modelling of radio spectra is also needed to understand

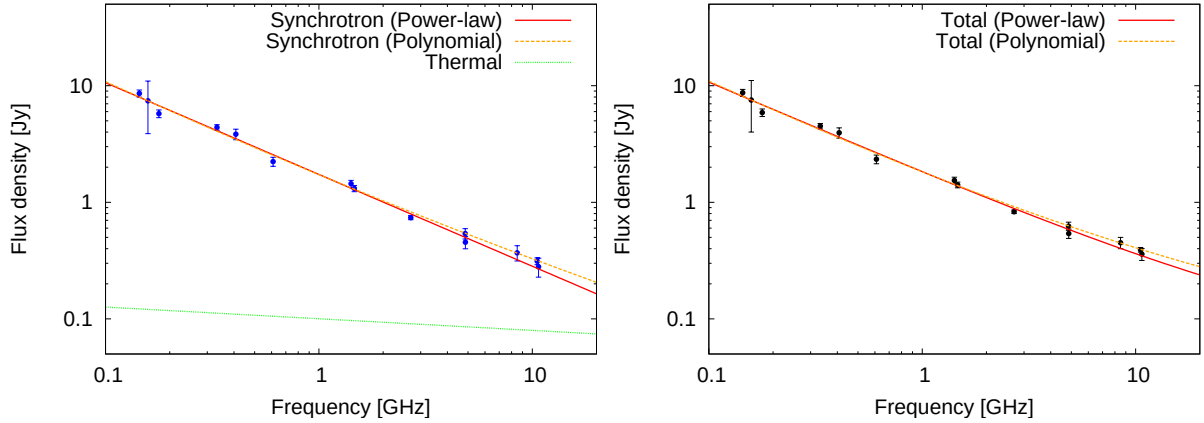


Figure 2.5: Spectrum of the integrated synchrotron and total flux density of NGC 6946. (Left) Spectrum of the synchrotron flux density obtained after subtracting the estimated thermal emission is shown as blue points. The thermal spectrum is presented as green dotted line. The red solid line and orange dashed line show the best power-law and polynomial model fitted to synchrotron flux densities, which were used to reconstruct the integrated spectrum shown in the right panel. (Right) Spectrum of the total flux densities is shown as black points. The integrated spectrum as a sum of thermal and synchrotron spectra modelled as power-law is shown as red solid line, while the model of integrated spectrum as a sum of thermal spectrum and synchrotron spectrum in a form of polynomial is presented as orange dashed line.

role of free-free absorption in the normal nearby galaxies. Such a modelling should involve different distributions of gas density within the galaxy disk in order to reconstruct total spectrum basing on various local spectra.

2.4.2 Local radio spectrum from the galaxy centre

The most dense ionized gas in galaxies is associated with the giant HII regions in the spiral arms and in the central region (nucleus). One can expect that a significant amount of free-free absorption should be seen towards such regions in the first place. Thus, local spectra may reveal spectral turnovers due to absorption in ionized gas at low frequencies. The nucleus of NGC 6946 is not resolved on the LOFAR map at 144 MHz. Therefore, for the purpose of constructing the local spectrum of the galaxy centre we measured only the peak fluxes at five frequencies. The available maps of radio emission at 0.33 (Basu et al. 2012), 1.4, 4.85 and 8.46 GHz from Beck (2007) were convolved to the resolution of the LOFAR map and transformed to the uniform grid. The obtained local spectrum for the nucleus of NGC 6946 is shown in Figure 2.6. The local spectrum below 333 MHz flattens towards 144 MHz with the observed spectral index of $\alpha_{low} = -0.32 \pm 0.02$, whereas beyond 1 GHz it is well modelled by a single power-law with spectral index of $\alpha_{high} = -0.60 \pm 0.01$.

The previous high-resolution radio observations of M82, a galaxy with high star-formation rate, revealed that its centre is a mixture of supernova remnants and ionized regions surrounding them (e.g. Fenech et al. 2010, Wills et al. 1997). Earlier studies of radio spectra of those independent sources from the centre of M82 showed that radio emission suffers from free-free absorption. The centre of NGC 6946 is not resolved at 144 MHz, but here we also believe that radio emission comes from a mixture of supernova remnants and ionized regions. We attempted to fit the spectrum of the nucleus applying

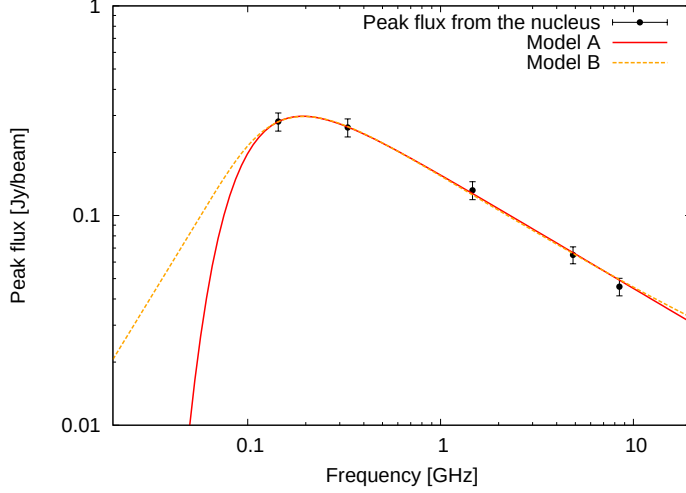


Figure 2.6: Local spectrum of the galaxy centre. Model A (red solid line) assumes that all synchrotron emission passes through ionized gas and undergoes free-free absorption. Model B (orange dotted line) describes a spectrum from well-mixed synchrotron and thermal emitting gas.

the model (see Equation 1.16), which was also used by Wills et al. (1997) for modelling free-free absorption in the local radio spectra of SNRs in M 82. In this model (hereafter called Model A), radio emission from a background source (supernova remnants) travels through ionized gas (foreground source) and it is attenuated by free-free absorption. The observed flux density is described by the following solution of the radiative transfer equation: $S_\nu \propto \nu^{\alpha_{nt}} \exp(-\tau_\nu)$, where τ_ν is the free-free optical depth at an observed frequency ν given by:

$$\tau_\nu = 0.082 \left(\frac{T_e}{\text{K}} \right)^{-1.35} \left(\frac{\nu}{\text{GHz}} \right)^{-2.1} \left(\frac{EM}{\text{cm}^{-6} \text{pc}} \right) \quad (2.1)$$

The temperature of the thermal electrons T_e is assumed to be 10^4 K (Tabatabaei et al. 2013), and EM is the emission measure ($EM = \int n_e^2 dl$, where n_e denotes the electron density of the ionized medium).

The best fitted model ($\chi_{red}^2 = 1.92 \times 10^{-5}$, $ndf = 2$) is shown as the solid red line in Figure 2.6. The obtained spectral index equals $\alpha_{nt} = -0.54 \pm 0.02$ and the emission measure of ionized gas required for the observed turnover of spectrum is $(2.5 \pm 0.20) \times 10^4 \text{ cm}^{-6} \text{ pc}$.

Alternatively, according to the model proposed by Condon (1992), the observed radio emission might come from synchrotron and thermal emitting gas, occupying the same volume. A solution of the radiative transfer equation for well-mixed synchrotron- and thermal-emitting gas can be approximated by the following model (hereafter called Model B):

$$S_\nu \propto T_e \nu^2 (1 - e^{-\tau_\nu}) \left(1 + \frac{1}{f_{th}} \left(\frac{\nu}{\text{GHz}} \right)^{0.1 + \alpha_{nt}} \right) \Omega \quad (2.2)$$

where, T_e is the temperature of thermal electrons, $\tau_\nu \propto \nu^{-2.1} EM$ is the free-free optical depth, f_{th} is the thermal fraction at 1 GHz and Ω is the solid angle subtended by the source.

The model gives the best fit ($\chi_{red}^2 = 3.20 \times 10^{-5}$, $ndf = 2$) when the thermal fraction is about 12% at 1 GHz and with the emission measure of $(6.12 \pm 0.53) \times 10^4 \text{ cm}^{-6} \text{ pc}$.

Both the models A and B of spectrum from the nucleus predict that the flux density should decrease below 144 MHz due to free-free absorption. The model of emission from a well-mixed synchrotron and thermal gas (Model B) shows a more gradual fall-off of flux density. However, it is not possible to distinguish which model is more reliable with data currently available. Future observations at lower frequencies e.g. with the LOFAR in LBA at around 50 MHz can be of indispensable in understanding the role of free-free absorption at local (small) scales.

We investigated also influence of the spatial resolution of observation on radio spectrum by comparing the spectrum constructed as above with the integrated spectrum of the central $40''$ region. The integrated spectrum of the central region showed a weaker flattening below 0.33 GHz, which suggests the importance of spatial resolution of observations needed for detailed studies of free-free absorption process at low frequencies. Investigation of physical scales at which free-free absorption is most effective requires high-resolution and sensitive observations at low frequencies. Quite recently, first results from observations with the LOFAR involving international baselines have become available (Varenius et al. 2015) and future observations can provide still more data.

2.4.3 Thermal and synchrotron emission of NGC 6946

The observed radio emission consists of the synchrotron and free-free (thermal) emissions. In order to measure the synchrotron intensity I_n and the magnetic field strength, we subtracted the free-free emission. This step is also essential in investigating energy losses of CREs using the synchrotron spectral index distribution (see Section 2.4.4).

To separate thermal emission from the observed radio emission map at 144 MHz, we used the thermal map at 1400 MHz (Tabatabaei et al. 2013) based on an $\text{H}\alpha$ image corrected for internal extinction, calculated from $24 \mu\text{m}$ dust emission. The integrated thermal flux density of 97 mJy constitutes 6.7% of the integrated total emission at 1400 MHz. The thermal map at 1400 MHz was scaled to the 144 MHz map using the constant spectral index $\alpha_{th} = -0.1$ corresponding to the thin thermal emission across the galactic disk. However, in the dense regions in the disk of NGC 6946 this assumption may be not fulfilled, leading to overestimation of the thermal emission. Then, the thermal map was convolved and placed onto the same grid as the LOFAR map. We obtained the synchrotron emission map at 144 MHz by subtracting the scaled thermal map from the LOFAR map.

The thermal and synchrotron maps at 144 MHz are presented in Figure 2.7. The thermal emission shows radiation from HII regions grouped in clumps and the most bright emission from the galactic centre. The integrated thermal flux density at 144 MHz of 121 mJy corresponds to the thermal fraction of 1.4% at this frequency. Therefore, due to low thermal fraction at 144 MHz, the synchrotron emission seen in Figure 2.7 (right panel) is similar to the total radio emission presented in Section 2.3. The low-frequency synchrotron emission of NGC 6946 has a form of bright nucleus and smooth disk surrounded by an envelope of weak radio emission.

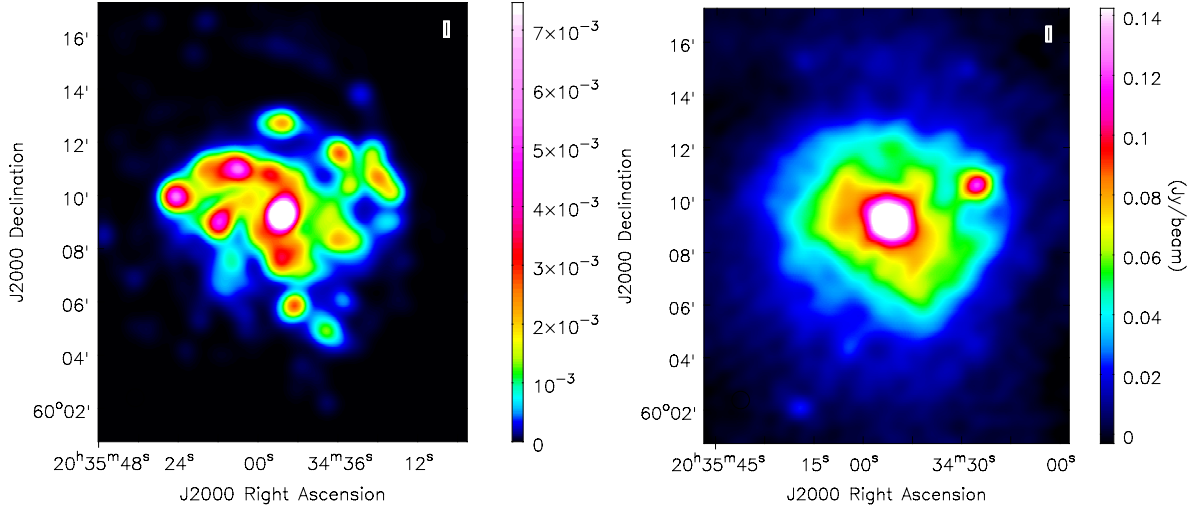


Figure 2.7: (Left) Thermal radio emission map of NGC 6946 at 144 MHz. (Right) Synchrotron radio emission map of NGC 6946 at 144 MHz. Both the maps have spatial resolution of $40''$, and the colour bars denote radio intensities in Jy/beam.

We also created the thermal fraction map at 144 MHz (Figure 2.8, left panel), which was computed from the thermal and the total radio emission maps at the same resolution of $40''$. In the right panel in Figure 2.8, the histogram of thermal fraction at 144 MHz is shown.

The thermal fraction values within the disk are usually in the range between 4 to 8% in the nucleus and in HII regions. The thermal fractions at 144 MHz are lower than typical thermal fractions in the giant HII regions (20 to 41%) determined at 1400 MHz (Tabatabaei et al. 2013). The obtained values of thermal fraction should be regarded as upper limits since the free-free absorption in the disk can reduce the synchrotron emission at 144 MHz, leading to overestimation of thermal fractions. Therefore, further observations at lower frequencies than 144 MHz are required to investigate the role of free-free absorption. Additionally, 3D modelling of free-free absorption by ionized gas in galactic disk with new high resolution low-frequency observations are needed to correct the free-free absorbed synchrotron emission.

2.4.4 Total and synchrotron spectral index distribution

The synchrotron spectral index α_{nt} of synchrotron emission ($\propto \nu^{\alpha_{nt}}$) is related to the spectral index p of energy spectrum of CREs ($\propto E^p$) injected into a galaxy via supernova remnants (Section 1.3.1). Distribution of synchrotron spectral index constitutes an important parameter in our understanding of propagation and energy loss mechanisms of CREs in the ISM. However, it is not possible to directly measure only the synchrotron spectral index, while the total spectral index is contaminated by thermal emission. Low-frequency radio emission is less affected by thermal emission than observations at higher frequencies and allows for studies of low-energy population of CREs.

The LOFAR map at 144 MHz and the map at 1400 MHz (Beck 2007) were used to construct the total spectral index map between these frequencies. We convolved the

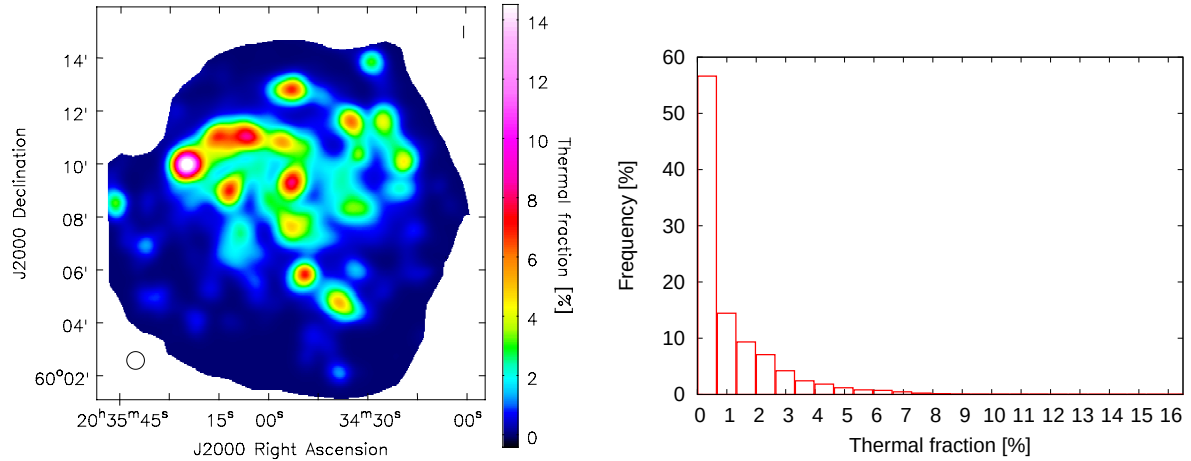


Figure 2.8: (Left) Map of thermal fraction at 144 MHz in the disk of NGC 6946. (Right) Frequency of thermal fraction at 144 MHz.

1400 MHz map to the same spatial resolution ($40''$) and adjusted to the same grid as the LOFAR map at 144 MHz. Next, we removed the background point sources from the map by fitting and subtracting Gaussian models of their emission. The total spectral index map between 144 and 1400 MHz presented in Figure 2.9 (left panel) was computed only for pixels with a signal to noise ratio (S/N) at least above three at both frequencies. The total spectral index varies from -0.32 in the nucleus to values less than -1.0 in the outskirts of the galaxy. It is remarkable that our total spectral index map is well correlated with the thermal emission shown in Figure 2.7 (left panel). Apart from the nucleus, flat spectra appear also in the giant HII regions ($\alpha < -0.5$) as well as the regions that follow a spiral-arm structure seen in $H\alpha$ emission.

We also obtained the synchrotron spectral index map (Figure 2.9, right panel) using the synchrotron radio emission map at 144 MHz (Figure 2.7, right panel) and synchrotron radio emission map at 1400 MHz, created by subtracting the scaled thermal map at 1400 MHz from obtained total radio emission at the same frequency. The synchrotron spectral index map was obtained in the same way as described above for the total spectral index map. The overall trend of values of the synchrotron spectral index from the galactic centre to the outskirts is very similar to that seen on the total spectral index map. However, in the nucleus a more flat spectrum can be seen in the distribution of the total spectral index than in the synchrotron spectral index. Generally, the synchrotron spectral index map shows less regions with a flat spectrum than in distribution of the total spectral index, particularly in HII regions.

The frequencies of values of the total and synchrotron spectral indexes distribution are also shown as histograms in Figure 2.10 (left panel). For the total spectral index they have the mean value of -0.89 ± 0.02 and the median value of -0.84 ± 0.02 , while the synchrotron spectral index mean and medial values are -0.92 ± 0.05 and -0.87 ± 0.04 , respectively.

The previous studies of the total spectral index of NGC 6946 by Klein et al. (1982),

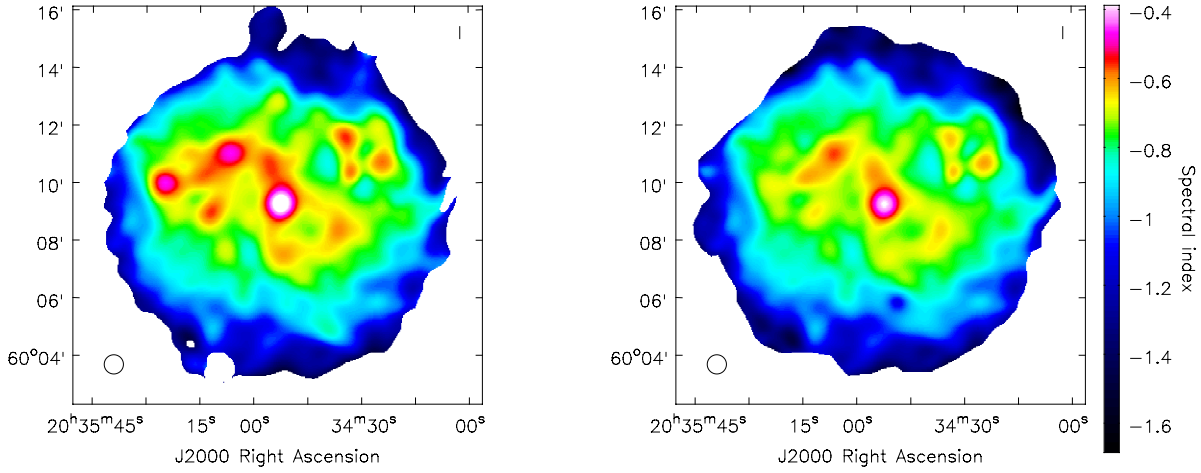


Figure 2.9: (Left) Total spectral index map of NGC 6946 between 144 and 1400 MHz. (Right) Synchrotron spectral index map of NGC 6946 between 144 and 1400 MHz. Both maps are in the same colour scale shown as the colour bar on the right and at a resolution of $40''$.

based on radio emission at 0.61 and 10.7 GHz, revealed an overall trend of spectral index from about -0.55 in the nucleus to about -0.9 towards the outskirts of NGC 6946. The total spectral index studied by Basu et al. (2012) at lower frequencies between 0.33 and 1.46 GHz showed a similar variation from about -0.45 in the central region to -1 towards the edge. The results suggest that towards low frequencies we observe regions with greater values of spectral indexes in the galactic centre. Our total spectral index map of NGC 6946 reveals that the spectrum of the nucleus is the most flat one with the spectral index of -0.32 , which supports this trend up to 144 MHz. We should expect a very similar effect, flattening of spectrum at lower frequencies, in the giant HII regions in the spiral arms. Moreover, correlation of values of total spectral indexes (> -0.5) between 144 and 1400 MHz with the thermal emission let us postulate that the observed flattening of spectrum is due to free-free absorption.

2.5 Radial profiles of radio emission and spectral indexes

Radio observations at two frequencies allow us also to analyse the average trend of spectral indexes with distance from the galactic centre. The radial profile of spectral indexes provide more general information on population of CREs (their propagation, and energy loss mechanisms) as well as on influence of ionized gas, which is more convenient while comparing results with other galaxies.

We constructed a radial profile of the total and synchrotron spectral indexes (Figure 2.10, right panel) from the mean flux densities at 144 and 1400 MHz as measured on the total and synchrotron radio emission maps in concentric rings with width of $40''$, taking into account the projection of the NGC 6946 disk on the sky (Table 2.1).

The radial profile of total and synchrotron spectral indexes quite rapidly drops off in the central part of the galaxy ($R \leq 3$ kpc). Subsequently, the values of total spectral

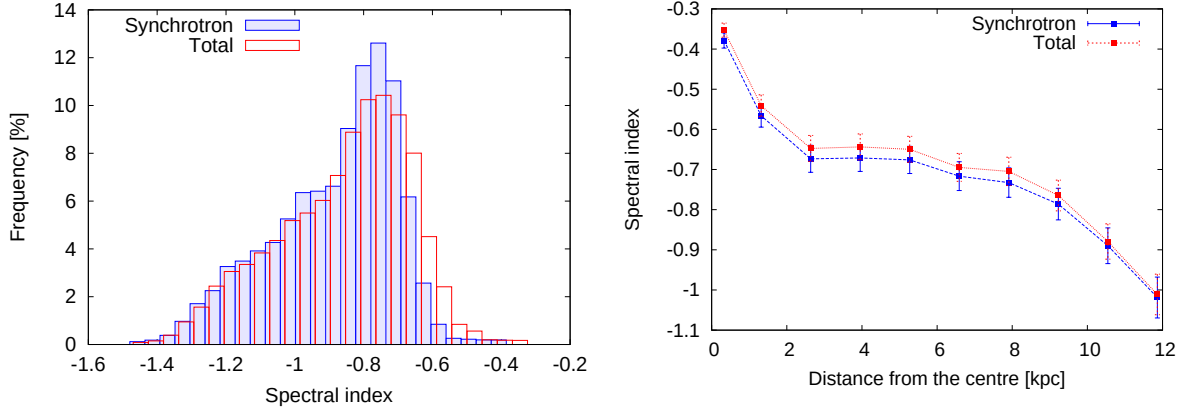


Figure 2.10: (Left) Frequency of the total (red) and synchrotron (blue) spectral index values of NGC 6946 between 144 and 1400 MHz. The mean and median values of distribution of total (synchrotron) spectral index are -0.89 ± 0.02 and -0.84 ± 0.02 (-0.92 ± 0.05 and -0.87 ± 0.04), respectively. (Right) Radial profile of the total (red) and synchrotron (blue) spectral index of NGC 6946 between 144 and 1400 MHz.

index show a plateau at 3 to 6 kpc from the centre due to thermal radiation of ionized gas from the spiral arms. Typical mean values of emission measure in this range of distances are from about 400 to 200 pc cm^{-6} . A similar behaviour can be seen in the synchrotron spectral index because of injection of fresh CREs from star-forming regions. In this range of radii, the total spectral profile is located above the synchrotron spectral index due to presence of thermal emission, which flattens the local spectra. At larger radii, both the total and synchrotron spectral index values start to decrease gradually due to lower number of star-forming regions and ionized gas. Furthermore, synchrotron and IC losses of CREs and diffusion become more important in the outskirts of NGC 6946.

The radial profile of the total and synchrotron spectral indexes of NGC 6946 between 333 and 1400 MHz obtained by Basu et al. (2012) shows a similar trend. Mulcahy et al. (2014) performed an analysis of radial profile of the total spectral indexes between 150 and 1400 MHz for different galaxy - M 51. In the central region of M 51, within a central few kpc, the radial profile of spectral indexes behaves in an analogous way as of NGC 6946, rapidly dropping off near the nucleus and then becoming flat in the region of spiral arms. However, beyond 10 kpc steepening of spectrum in the outskirts of M 51 is more pronounced than in NGC 6946.

The radial distribution of synchrotron radio emission and their scale length of face-on galaxies is a vital tool for analysing propagation and energy-loss mechanism of CREs in the galactic disk. The scale length L of synchrotron radio emission approximated by an exponential function given by $I_\nu \propto \exp(-r/L)$ (see Appendix C) and determined at different frequencies lets us test various models of CREs propagation. The low-energy CREs observed at low radio frequencies are less affected by energy loss mechanisms than those at higher frequencies. Therefore, the radio emission of galaxies should be more extended, and the low-frequency scale length should be greater too. Data below 300 MHz have never been used for such an analysis of NGC 6946, because sensitivity and angular resolution of previous low-frequency observations were insufficient.

We obtained the radial profile of the synchrotron radio emission at 144 and 1400 MHz

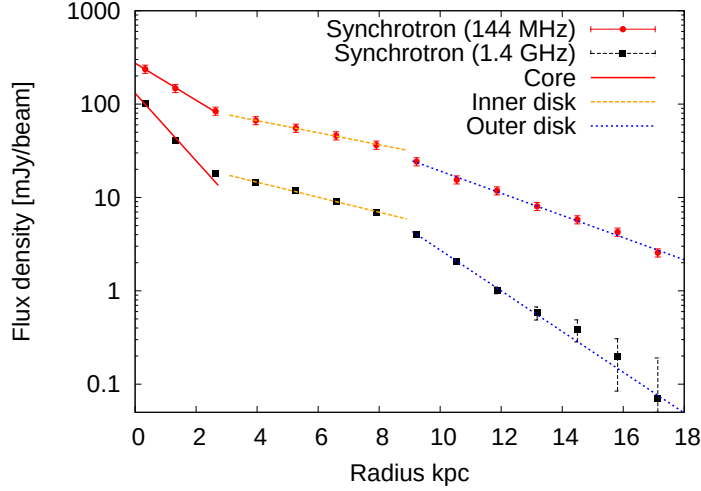


Figure 2.11: Mean radial profile of synchrotron radio emission of NGC 6946 at 144 and 1400 MHz.

from the mean in concentric rings with the position angle of the major axis and the inclination of NGC 6946 (see Table 2.1). The influence of background point sources was removed by fitting Gaussian components and their subtraction from both the maps. Figure 2.11 shows radial profiles of synchrotron radio emission at 144 and 1400 MHz. They can be described by three components: the core, the inner disk (3 - 8 kpc), and the outer disk beyond the galactocentric distance of about 9 kpc. The scale lengths for those components were determined separately by fitting the following exponential functions at 144 and 1400 MHz map:

$$I(r) = \begin{cases} I_c \exp(-r/L_{core}) & r < 3 \text{ kpc} \\ I_{in} \exp(-r/L_{inner}) & 3 \leq r < 9 \text{ kpc} \\ I_{out} \exp(-r/L_{outer}) & r \geq 9 \text{ kpc} \end{cases} \quad (2.3)$$

The best-fit models are shown in Figure 2.11 and the obtained corresponding scale lengths are provided in Table 2.4. We reveal two breaks in radio profiles of synchrotron radio emission at 144 MHz. The first break corresponds with the transition between thin and thick galactic disks. The second break is a decline of exponential scale length to 3.65 for a radius beyond 9 kpc at 144 MHz, which is about 2 times smaller than the scale length for the inner disk. This break cannot result from lack of short spacings, and thus the lack of sensitivity to extended structure, since the LOFAR has an excellent UV-coverage in the inner part of the interferometer. Therefore, the smaller scale length of the outer disk must be caused by a sharp decrease in the number of star-forming regions and sources of CREs.

Table 2.4: Scale length of the core, inner and outer disk at 144 and 1400 MHz.

Freq. GHz	Core kpc	Inner disk kpc	Outer disk kpc
0.144	2.18 ± 0.08	6.71 ± 0.22	3.65 ± 0.17
1.4	1.19 ± 0.14	5.41 ± 0.34	1.99 ± 0.06
Ratio	1.83 ± 0.27	1.24 ± 0.24	1.83 ± 0.23

A similar shape of the radial profile of the radio emission was also found in other galaxies as, M33 (Tabatabaei et al. 2007) and M51 (Mulcahy et al. 2014). The ratio of about 2 between the scale length for the inner and outer disk is consistent with the results obtained by Tabatabaei et al. (2007) for M33. LOFAR observation of M51 at 150 MHz (Mulcahy et al. 2014) revealed a similar break in radial profile with the ratio of 2.6 between the scale lengths for the inner and outer part of the disk. Further discussion of these results is given in Section 2.7.3.

2.6 Magnetic field strength

LOFAR observations of galaxies allow to estimate strength of magnetic fields only minimally affected by thermal emission, which becomes significant at higher frequencies. Previous extensive studies of magnetic fields above 1 GHz required removal of thermal emission (typically 10% at 1.4 GHz). Separation of thermal emission is a complex process relying on $H\alpha$ and 24 μm dust emissions. Thermal emission is negligible at low radio frequencies, so that estimated values of magnetic field are more reliable, especially in the galaxy outskirts, where radio emission is also less affected by free-free absorption.

The total magnetic field strength of NGC 6946 can be calculated assuming the energy equipartition between cosmic-ray particles and magnetic field. The “revised” formula (Beck & Krause 2005) lets us estimate the equipartition field strength B_{eq} as follows:

$$B_{eq} = \left\{ 4\pi(K_0 + 1)E_p^{1-2\alpha_{nt}} \frac{f(\alpha_{nt})}{c_4(i)} \frac{I_\nu \nu^{\alpha_{nt}}}{l} \right\}^{1/(\alpha_{nt}+3)} \quad (2.4)$$

where K_0 is the ratio of number density of relativistic protons and electrons, E_p denotes the rest mass energy of protons, α_{nt} is the synchrotron spectral index, and I_ν is the synchrotron intensity at frequency ν . The path-length through synchrotron emitting region is denoted by l . The constant $c_4(i)$ takes into account the inclination of the magnetic field, and the function $f(\alpha_{nt})$ is given by $f(\alpha_{nt}) = (2\alpha_{nt} + 1)/[2(2\alpha_{nt} - 1)c_2(\alpha_{nt})c_1^{\alpha_{nt}}]$, where constants c_1, c_2 are to be found in Appendix of Beck & Krause (2005).

For the purpose of calculations we assumed that the synchrotron spectral index $\alpha_{nt} = -0.8$ (Condon 1992) and the effective path length through the source $1 \text{ kpc}/\cos(i) = 1.27 \text{ kpc}$. The ratio of CR proton to electron number density $K_0 = 100$ is a reasonable value for star-forming regions (Bell 1978), commonly used in calculating the magnetic fields in galaxies (e.g. Beck 2007, Mulcahy et al. 2014).

The mean value of galactic magnetic field strength calculated from the integrated synchrotron radio emission at 144 MHz is $10.8 \mu\text{G}$ (Table 2.5). Due to the low resolution of the LOFAR map at 144 MHz, it is not possible to obtain measurements in the arm and inter-arm regions. In the inner part of NGC 6946, the values of magnetic field strength decrease from about $19 \mu\text{G}$ within the nucleus to $11 \mu\text{G}$ at the distance of 10 kpc. We estimated how much changes of K_0 and the path-length can affect the calculated values of magnetic field strength, finding that modifying these parameters by a factor of 2 would change the results by 20%. Furthermore, an uncertainty of the spectral index of ± 0.1 leads to an error at the level of 5% in the results.

Table 2.5: Strength of magnetic fields within NGC 6946.

Region	Magnetic field
In nucleus	19.0 μG
At $R = 10$ kpc	11.0 μG
Mean value	10.8 μG

Previously low-frequency observations at 0.33 GHz by Basu & Roy (2013), were also used to calculate the magnetic field strength of NGC 6946. The authors obtained the mean value of magnetic field strength for the galaxy as a $10.7 \pm 1.8 \mu\text{G}$, which is in excellent agreement with the values determined from the LOFAR data. The magnetic field strength in the nucleus calculated from the radio emission at 144 MHz agrees well with typical the values 18 - 20 μG in the optical arms estimated at 1400 MHz by Beck (2007). However, it is lower than the magnetic field strength of 25 μG obtained by the same author in galactic centre. The difference can be caused by free-free absorption at 144 MHz or inaccurate determination of thermal component at 1400 MHz in the work of Beck (2007).

2.7 Discussion

2.7.1 Free-free absorption in the disk of NGC 6946

A number of turnovers in the integrated radio spectra have been observed in the nearby starburst galaxies. They occur at about 500 MHz for M82 (Adebahr et al. 2013), and at a lower frequency of 230 MHz for NGC 253 (Kapińska et al. 2017). Moreover, the galaxies known as luminous infrared galaxies (LIRGs) and ultra-luminous infrared galaxies (ULIRGs) also reveal multiple turnovers in their integrated radio spectra, presumably be caused by free-free absorption of the dominant synchrotron sources in the galaxy disk (Clemens et al. 2010). The studies of spatially resolved sources at LOFAR 154 MHz (Varenius et al. 2015) and at 408 MHz (Wills et al. 1997) also demonstrated importance of free-free absorption locally within the galaxy disk of M 82. Contrary to the commonly observed turnovers of integrated radio spectra of the galaxies with a high star-formation rate, it is still debatable if such effects can be also found in the normal galaxies.

We analysed the global spectrum of the total and synchrotron flux density (Figure 2.5) of NGC 6946 using flux density measurements from our LOFAR observations at 144 MHz (Section 2.4.1). The previous studies of integrated spectrum of NGC 6946 down to 333 MHz (Basu et al. 2012) claimed that there is no flattening or spectral turnover towards low frequencies. We investigated a potential curvature of the synchrotron spectrum (Figure 2.5, left panel) using an empirical model with a second-order polynomial and also did not find any indication of flattening down to 144 MHz due to free-free absorption or ionization losses. The best model fit to data for the synchrotron spectrum was achieved by applying a simple power-law, while a model involving spectrum curvature (second-order polynomial) gave worse results (Section 2.4.1). Towards higher frequencies, we did not observe either steepening or spectral break in the synchrotron spectrum. Pohl et al. (1991) proposed a model predicting an energy break in the CRE energy spectrum re-

sulting from various kinds of energy losses of CREs (synchrotron loss, inverse-Compton loss, non-thermal bremsstrahlung loss and adiabatic expansion). The authors concluded that the integrated spectrum of NGC 6946 was well approximated by a single power-law, and there could possibly occur a spectral break at very low frequencies below 50 MHz. However, their model did not take into account free-free absorption.

The integrated radio spectrum of NGC 6946 (Figure 2.5, right panel) revealed only some flattening towards the higher frequencies caused by increasing thermal emission seen beyond 8 GHz. Klein et al. (1982) estimated the upper limit of the thermal fraction of 30% at 10.7 GHz. Below 0.33 GHz, the thermal fraction is presumably lower than 4.3% (Basu et al. 2012). Using the thermal emission map at 1.4 GHz in calculating the thermal flux density at 144 MHz (Section 2.4.3), we obtained the integrated value of 121 mJy, which corresponds to the thermal fraction of 1.4% at this frequency.

The total and synchrotron spectral index maps of NGC 6946 between 144 and 1400 MHz, analysed in Section 2.4.4, reveal regions with flatter spectrum than typical injected spectra of CREs ($\alpha = -0.6$). These regions are correlated with the location of giant HII regions and the nucleus. Significantly flatter spectrum than the injected one ($\alpha = -0.6$) is unlikely to be caused by synchrotron-self absorption, which can be of importance only for very compact sources as radio supernovae (Chevalier 1998). The observed values of spectral index higher than -0.5 are found in the nucleus and towards giant HII regions in the inner disk. Correlation with the location of dense ionized gas supports the prediction of Lacki (2013) that free-free absorption is the dominant process within HII regions, observed down to low frequencies of about 10 MHz.

Our analysis of the local spectrum from the nucleus of NGC 6946 (Section 2.4.2) revealed flattening below 0.33 GHz. In order to reconstruct the local spectrum, we applied two spectral models (Figure 2.6). One of them assumes that synchrotron emission is seen through a ionized gas. The observed spectral turnover caused by free-free absorption in this model requires the emission measure of ionized gas of $(2.5 \pm 0.20) \times 10^4 \text{ cm}^{-6} \text{ pc}$. The other model, involving radio emission from well-mixed synchrotron and thermal emitting gas with free-free absorption, is also in good agreement with the observed spectrum from the nucleus. It requires higher values of emission measure from the nucleus as $(6.12 \pm 0.53) \times 10^4 \text{ cm}^{-6} \text{ pc}$. Both models predict a decrease of flux density below 144 MHz, however the latter shows a more gradual drop-off than the former. To decide which of them is more reliable, further observations of NGC 6946 at lower frequencies are needed. Basu et al. (2012) showed for the sample of 5 galaxies, including NGC 6946, that the typical values of EM from the galaxy centre and HII regions lie in the range from a few times 10^3 to a few times $10^4 \text{ cm}^{-6} \text{ pc}$, and decrease to values from few tens to few hundreds $\text{cm}^{-6} \text{ pc}$ at larger distances from the galactic centre. For values of emission measure of 100 and $10^4 \text{ cm}^{-6} \text{ pc}$ the optical depths τ_ν at 144 MHz are 0.002 and 0.02 respectively, which can lead to reducing synchrotron emission at 144 MHz by only $(1 - \exp(-0.002)) \times 100\% = 0.2\%$ and about 2%, respectively. At lower frequency of 50 MHz, the same ionized gas with emission measure of $10^4 \text{ cm}^{-6} \text{ pc}$ can absorb up to 83% of synchrotron emission due to free-free absorption. Therefore we think that the normal star-forming galaxies observed at lower frequencies, of about 50 MHz, should manifest much stronger effects of free-free absorption, particularly in local spectra.

Recently, two other galaxies with different inclinations, M 51 (face-on) and NGC 891 (edge-on), were observed with the LOFAR in HBA (Mulcahy et al. 2014, 2018). Similarly to NGC 6946 the integrated spectrum of M 51 shows no indication of flattening down to 150 MHz. The integrated spectrum of NGC 891 did reveal curvature, however, the authors were not able to identify an underlying physical mechanism. Therefore further observations at lower frequencies are crucial. We would suggest the LOFAR LBA measurements at around 50 MHz to constrain the role of free-free absorption in shaping integrated radio spectra of nearby star-forming galaxies.

Our study of NGC 6946 at 144 MHz revealed that there is no free-free absorption effect in the integrated spectrum, while it is found in the local spectrum of the galaxy centre. The spectral index maps disclosed regions of flatter spectrum than the injected spectra of CREs. This shows that free-free absorption is present at local scales in the disc of NGC 6946, but does not affect the integrated spectrum down to 144 MHz. The physical properties of the ISM vary from one region to another in the galaxy disk, and the integrated spectrum is constructed from the emission of all regions, having different physical properties and different local radio spectra. Therefore, we are of opinion that comprehensive modelling of radio emission of galaxies is required to properly interpret low-frequency radio spectra. Such a modelling would help to constrain the role of free-free absorption in physical scales from individual HII regions to the whole galaxy, as well to assess influence of relative distribution of thermal and synchrotron emitting gas. Apart from physical conditions, the modelling could also predict impact of projection effects and spatial resolution of observations on the integrated spectrum and local spectra of galaxies.

2.7.2 CREs energy loss mechanisms in the disk of NGC 6946

Our analysis of the synchrotron spectrum of NGC 6946 showed that it is well modelled by a simple power-law (Section 2.4.1). This finding can suggest that the energy loss mechanisms of CREs, which possibly lead to steepening of spectral break at higher frequencies, and flattening towards low frequencies, are not efficient enough to modify the spectrum of integrated synchrotron flux density of NGC 6946. However, these processes can play an important role in shaping of local spectra, especially in dense gas regions and at the outskirts of the galactic disk.

A population of CREs injected into galaxy via supernova remnants (SNR) undergo different energy loss processes, such as synchrotron, IC, non-thermal bremsstrahlung and ionization. Both the synchrotron and IC energy losses cause the spectral steepening at high frequencies, while ionization losses can flatten the synchrotron spectrum towards low frequencies.

The maximal contribution to synchrotron emission at the frequency ν comes from CREs at the energy, which can be calculated from Equation 1.2. Assuming an isotropic turbulent field, the component of total magnetic field strength in the sky plane ($B_{\perp}$) can be approximated by $\sqrt{2/3}B$, where B is the total magnetic field strength. The synchrotron radiation of NGC 6946 seen in the LOFAR HBA at 144 MHz comes from CREs with energy of about 1 GeV for the mean magnetic field strength in NGC 6946 (Section 2.6) of about 11 μ G, and from energies above 0.75 GeV in the spiral arms where the magnetic

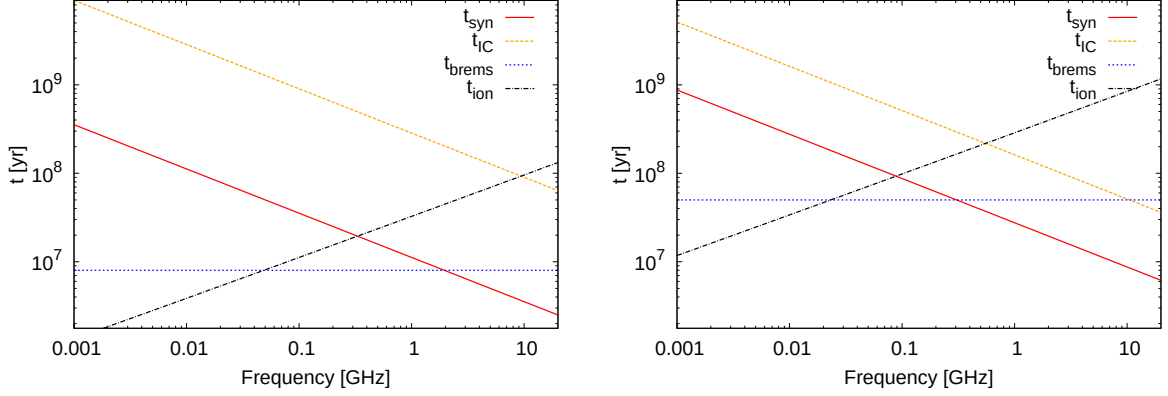


Figure 2.12: (Left) The timescales of synchrotron, inverse-Compton, non-thermal bremsstrahlung and ionization losses for the conditions present in the nucleus of NGC 6946 assuming strength of magnetic field of $25 \mu\text{G}$ and neutral gas density about of 5 cm^{-3} . (Right) The synchrotron, inverse-Compton, non-thermal bremsstrahlung and ionization loss timescales as a function of frequency calculated for the mean physical parameters of NGC 6946, assuming strengths of magnetic fields of $11 \mu\text{G}$ and atomic hydrogen densities of about 0.8 cm^{-3} .

field strength is up to about $20 \mu\text{G}$.

Below we discuss significance of different energy loss mechanisms of CREs, which take place in the disk of NGC 6946, using their timescales at 144 MHz (see Appendix A). The synchrotron timescale, described by the half-power lifetime of the observable synchrotron emitting CREs (cf. Table A.1), is about 0.86×10^8 years for the mean value of the total magnetic field strength in the disk of NGC 6946, and above 0.3×10^8 years in the spiral arms.

The CREs lose their energy also due to scattering by the radiation field in the galaxy, which results from the infrared and stellar radiation field and the cosmic-ray microwave background field. This process is known as inverse-Compton radiation losses (see Appendix A). Both the synchrotron (t_{syn}) and IC (t_{IC}) energy loss timescales of CREs have the same dependence on energy and separating their individual contributions to the synchrotron spectrum is difficult. However, their combined action results in steepening of the spectrum at high frequencies. Typically, t_{syn} is smaller than t_{IC} in normal galaxies, and their ratio varies from 10% to 80% (Heesen et al. 2018). The IC timescales can be shorter than the synchrotron radiation timescales only in regions of weak magnetic and radiation fields, which occur in outer parts of the galactic disk, where gas density is low. Using typical values of the total photon energy of radiation field for nearby star-forming galaxies of $10^{-12} \text{ erg cm}^{-3}$ (Murphy 2009), we obtained the IC timescale of 4.5×10^8 years in the disk of NGC 6946, and shorter than 6.0×10^8 years in the spiral arms of NGC 6946.

Both non-relativistic bremsstrahlung and ionization loss, and their timescales t_{brems} and t_{ion} , depend on the density of neutral gas (see Appendix A). Distribution of the neutral gas surface density Σ_{gas} of NGC 6946 revealed high densities up to about $240 \text{ M}_{\odot} \text{ pc}^{-2}$ in the nucleus to $20 - 45 \text{ M}_{\odot} \text{ pc}^{-2}$ along the optical spiral arms (Crosthwaite & Turner 2007). The authors also determined the mean value of surface gas density of the NGC 6946 disk without the nucleus, which equals to about $13 \text{ M}_{\odot} \text{ pc}^{-2}$. Usually the surface density of gas traced by neutral hydrogen emission is below $10 \text{ M}_{\odot} \text{ pc}^{-2}$ for the nearby star-forming galaxies (Leroy et al. 2008), while higher surface densities originate entirely from

molecular gas, which is detected by CO line.

We used the above results to calculate the mean density of neutral gas in the nucleus and in the whole disk of NGC 6946. Following the calculations described by Basu et al. (2015), we also assumed a 3-component vertical distribution of the HI (Dickey & Lockman 1990) and a single exponential component for the molecular gas (Sanders et al. 1984), like in the Milky Way. The obtained value allowed us to calculate the timescales of ionization and non-thermal bremsstrahlung losses as a function of frequency in the nucleus and in the disk of NGC 6946, which along with the synchrotron and IC timescales for the nucleus and the galaxy disk, are presented in Figure 2.12.

Ionization losses (black dash-dotted line in Figure 2.12), which can lead to flattening of the synchrotron spectrum of NGC 6946, start to dominate synchrotron energy loss processes below 300 MHz in the nucleus and below about 100 MHz in the disk of NGC 6946, which suggests that the flattening of the local spectrum in the nucleus of NGC 6946 (Figure 2.6) seen at 144 MHz can be partially due to ionization losses and free-free absorption. More radio data at lower frequencies (< 100 MHz) are necessary to determine the relative influence of both the processes on the shape of local spectra in NGC 6946 and similar galaxies.

2.7.3 CREs diffusion in NGC 6946

We obtained the scale lengths of the synchrotron emission of NGC 6946 at 144 MHz, which are larger than those determined at 1400 MHz (Section 2.5). Moreover, the scale lengths of the synchrotron emission at 144 and 1400 MHz estimated for the inner and outer disk of NGC 6946 differ by a factor of 1.24 and 1.83 (Table 2.4), respectively. CREs, traced by synchrotron emission, can be transported through the ISM via either diffusion or advection in a galactic wind. Diffusion results from random scattering by irregularities in the turbulent magnetic field, and takes place in the typical star-forming galaxies, like the Milky Way (Strong et al. 2011), while transporting of CREs with gas in a galactic wind flow is usually observed in starburst galaxies.

In the case of diffusion, the propagation length of CREs depends on the diffusion coefficient D and the lifetime of CREs t_{CRE} and can be expressed as $L_{diff}(\nu) \propto \sqrt{D t_{CRE}}$ (e.g. Tabatabaei et al. 2013). In a general case, D can depend weakly on energy of the electrons beyond few GeV (Engelmann et al. 1990). The energies of electrons traced at 144 and 1400 MHz in the typical magnetic field in NGC 6946 are below the threshold of 4 GeV (see Section 2.7.2), and in further analysis we neglect the energy dependence of D . Assuming that the dominant process responsible for energy loss of CREs in the galaxy disk are synchrotron losses, the lifetime of CREs is $t_{CRE} = t_{sync} \propto B_{tot}^{-2} E^{-1} \propto B_{tot}^{-3/2} \nu^{-1/2}$ (see Equation 1.2 and Table A.1), where ν is the observation frequency. The CREs propagation scale length is then given by:

$$L_{diff}(\nu) \propto B_{tot}^{-3/4} \nu^{-1/4}. \quad (2.5)$$

We calculated the theoretical ratio of scale length $L_{diff}(144 \text{ MHz})/L_{diff}(1400 \text{ MHz})$, which is 1.77. In our analysis of the mean synchrotron scale length of NGC 6946 at 144 and 1400 MHz (Section 2.5), similar ratios of 1.24 ± 0.24 and 1.83 ± 0.23 for the inner and

the outer disk were obtained, respectively. Diffusion of CREs taking into account that CREs lifetime is limited by synchrotron losses, which predicts a value of 1.77, agrees well with the ratio determined by us for the outer disk of NGC 6946. The lower value of the ratio for the inner disk of NGC 6946 than the theoretical one can be caused by presence of CREs sources in the star-forming disk.

Basing on our calculations, we suggest that the principal mechanism of CREs propagation in the disk of NGC 6946 is actually diffusion. A similar conclusion yielded numerical simulations of propagations of CREs for another nearby galaxy, M 51 (Mulcahy et al. 2016). As synchrotron and IC losses of CREs are weaker at low frequencies, hence CREs' lifetime is larger and they can diffuse further from their origin sites. The diffusion combined with weaker synchrotron and IC loss of CREs well explains the more extended radio emission of NGC 6946 observed at 144 MHz than at high frequencies.

2.8 Conclusions

In this study, I investigated for the first time the radio continuum emission of the grand-design spiral galaxy NGC 6946 at 144 MHz, using the LOFAR HBA observations. The main findings of this work are summarized below:

- I have detected an envelope of weak radio emission surrounding the galaxy out to the radius of 18 kpc, more extended than the optical disk and the radio emission at higher frequencies (Section 2.3).
- The integrated spectrum of NGC 6946 does not flatten towards low frequencies, down to 144 MHz, which excludes strong free-free absorption or ionization losses of CREs (Section 2.4.1). The radio spectrum is described well by a single power-law, and does not reveal steepening nor spectral break at high frequencies resulting from synchrotron and IC radiation losses.
- The modelled local spectrum from the central parts of the galaxy flattens below 333 MHz, indicating free-free absorption of the synchrotron emission. However, further low-frequency and high-resolution observations of NGC 6946, at about 50 MHz, are desirable to confirm the decrease of flux densities below 144 MHz (see Figure 2.6). It can be seen also some indication of free-free absorption primarily caused by an ionized gas in the nucleus and in the HII complexes with the spectral indexes between 144 and 1400 MHz greater than -0.5 (Section 2.4.4), corresponding to the spectral index of freshly energized CREs.
- The analysis of CREs energy loss mechanisms in NGC 6946 indicates that ionization losses, leading to also flattening of spectrum at low frequencies, can dominate the synchrotron losses below 300 MHz in the nucleus and below about 100 MHz in the disk of NGC 6946, respectively (Section 2.7.2). Therefore, the observed flattening of the local spectrum in the nucleus of NGC 6946 can be caused by both the ionization losses and free-free absorption.

- Assuming equipartition, I estimate the mean galactic magnetic field strength in NGC 6946 as $10.8 \mu\text{G}$, which is comparable to the typical value of about $11 \mu\text{G}$ in regions at 10 kpc radius (Section 2.6). The magnetic field strength of $19 \mu\text{G}$ in the nucleus of NGC 6946 agrees well with the typical values 18 - $20 \mu\text{G}$ in the optical arms, estimated at 1400 MHz by Beck (2007). However, the value in the nucleus is lower than $25 \mu\text{G}$ obtained at 1400 MHz, presumably due to free-free absorption at 144 MHz or incorrect determination of thermal component at 1400 MHz in the work of Beck (2007).
- The scale lengths of the synchrotron emission are about twice larger at 144 MHz than those at 1400 MHz (Section 2.5). The radial profiles of the emission reveal two breaks. The first break at distance of about 3 kpc from the galactic centre corresponds with the transition between thin and thick galactic disks, while the second one between the inner and outer disks at about 9 kpc, can be ascribed to sudden disappearance of star-forming regions and sources of CREs. These results are in concordance with similar effects found in M 51 (Mulcahy et al. 2014).
- The carried out analysis of CREs propagation processes suggests that in NGC 6946 the most likely is the diffusion process (Section 2.7.3). This mechanism explains the extended radio halo observed in the LOFAR maps and the ratio of the observed scale lengths at 144 MHz and 1400 MHz.

In this study of NGC 6946 I underscore the need of further low-frequency observations. I submitted a proposal for observations of NGC 6946 with the LOFAR LBA at frequencies down to 30 MHz, which will probably enable me to detect radio emission even more extended than that at 144 MHz. I expect free-free absorption to become prominent at such low frequencies. The proposed project (LC4_013) was accepted, and the relevant observations have been already performed.

I established that free-free absorption at 144 MHz is present locally in the nucleus and in the HII complexes in the disk of NGC 6946. As the physical properties of the ISM can vary from one region to another within the galaxy disk, the local spectra can be significantly different. Moreover, CRE energy losses also depend on the local conditions of the ISM and can produce various breaks in the local spectra. I have shown also that the scale lengths of synchrotron emission can be frequency-depended. Therefore, in order to properly interpret the integrated spectra, a more advanced method is required - a 3D comprehensive modelling of radio emission. However, I have not encountered such a model in the literature to date. This was motivation for construction of such a model in this work (see next chapters).

CHAPTER 3

Simple model of radio emission of galaxies

3.1 Introduction

As I already wrote in Section 2.4.1, the integrated radio spectra of normal star-forming galaxies are shaped by relative contributions from thermal and synchrotron emissions. Thermal emission arises mainly from ionized gas in the form of HII regions located in spiral arms, while synchrotron emission traces the underlying distributions of CREs and magnetic fields. The integrated radio spectra can be approximated by a power-law model with a spectral index α related to the radiation process. Thermal emission from an optically thin medium can be characterized by $\alpha = -0.1$, while synchrotron emission has a more steep spectrum with $\alpha \approx -0.8$ (Condon 1992). Freshly energized CREs in the shock fronts of supernova remnants result in a synchrotron spectrum with $\alpha \approx -0.5$ (e.g. Bell 1978, Kothes et al. 2006). Combining both thermal and synchrotron emissions leads to a radio spectrum flatter than the synchrotron emission spectrum. In general, thermal emission constitutes of about 10% of the observed radio emission at 1.4 GHz in the normal star-forming galaxies, and becomes more important at higher frequencies. Thus, the integrated spectra often show flattening at higher frequencies due to the increased thermal component.

Low-frequency radio spectra can be modified by ionized gas in the HII regions, which can become optically thick and absorb not only free-free emitted photons but also the photons from synchrotron process. Furthermore, ionization losses at low frequencies can become more significant than at higher frequencies (see Section 1.4). This process can be even more important in the starburst galaxies, where high-density regions are coupled with high star-formation activity and give rise to spectral turnovers. Moreover, Lacki (2013) argued that the synchrotron self-absorption and Razin effects can lead to further reduction of radio emission from dense regions in the ISM and cause spectral turnover in the galaxy spectra at frequencies lower than 10 MHz.

Our current knowledge of processes that shape low-frequency radio spectra of galaxies is very limited, mostly due to lack of high-quality and systematic observations of galaxies at these frequencies. The first attempt of systematic observations of 68 galaxies with the Clarke Lake Telescope at 57 MHz (Israel & Mahoney 1990) provided some hints of free-free absorption. The authors found that flux densities at 57 MHz were systematically lower than expected (see Section 1.1), with the difference largest for the highly inclined

objects. However, Hummel (1991) reanalysed the data and came to different conclusions. He proposed that the observed spectral break is a result of the steepening of spectra at higher frequencies due to energy loss and propagation of CREs, which does not depend on the galaxy's viewing angle. Due to contradictory results and difficulties to obtain high-quality data at low frequencies, the actual role of free-free absorption remains still unclear (Marvil et al. 2015, Mulcahy et al. 2018).

Recently, the data from the first major observing program with the LOFAR, the MSSS, were used in studies of the integrated spectra of galaxies (Chyży, Jurusik et al. 2018). The authors determined flux densities at 150 MHz from both the MSSS source catalogue and direct measurements using the available sets of image mosaics for a sample of 129 nearby star-forming galaxies. Some integrated spectra from the sample revealed weak spectral curvatures, which were estimated by a difference between the low-frequency and high-frequency spectral indexes for each galaxy. The median value of such estimated spectral curvatures $\Delta\alpha$ is 0.18 ± 0.02 , which indicates a small but statistically significant flattening of the integrated spectra of galaxies towards low frequencies. We have shown that the spectral flattening does not depend on galactic morphology and is not related to inclination angle, which contradicts the findings by Israel & Mahoney (1990).

In the study presented in Chapter 2 I analysed the integrated spectrum of NGC 6946 using our LOFAR HBA observations at 144 MHz. Contrary to a number of starburst galaxies, the integrated spectrum of NGC 6946 appeared to be not affected by free-free absorption towards 144 MHz. Mulcahy et al. (2014) obtained a similar result that the integrated spectrum of another nearby star-forming galaxy, M 51, shows no evidences of spectral flattening down to frequency of 150 MHz.

Starburst galaxies as compared to typical star-forming galaxies manifest an exceptionally high star-formation rate, which can convert a large amount of its available gas into stars on a timescale much shorter than the galactic age. While the same physical processes are at work in all star-forming galaxies, the physical conditions within star-forming galaxies can differ significantly. In starburst galaxies one can find extreme environments with average gas densities and pressure hundreds of times greater than in nearby star-forming galaxy like the Milky Way. Such extreme conditions can alter the structure of the ISM, leading to changes in radiation processes and hence in the integrated spectra of starburst galaxies. The processes, which initiate a starburst must be able to concentrate a large amount of cool gas. It is believed that such concentration of medium can be triggered by interaction or collisions of galaxies. Spectral turnovers due to free-free absorption have been observed in the integrated spectra of well-known starburst galaxies in the local Universe: Arp 220 (Varenius et al. 2016), M 82 (Adebahr et al. 2013), and NGC 253 (Kapińska et al. 2017). All of them show evidences of post tidal interactions.

In this Chapter I aim to investigate how various physical parameters of galaxies influence their integrated radio spectra. For this purpose, I use 3D numerical model of radio emission of galaxies, which is described in Section 3.2. In Section 3.3, I apply the model to investigate the importance of density of ionized gas, the presence, size and intensity of synchrotron halo, synchrotron spectral index, and projection effects due to different viewing angles of galactic disks. The main conclusions of this study are presented in Section 3.4.

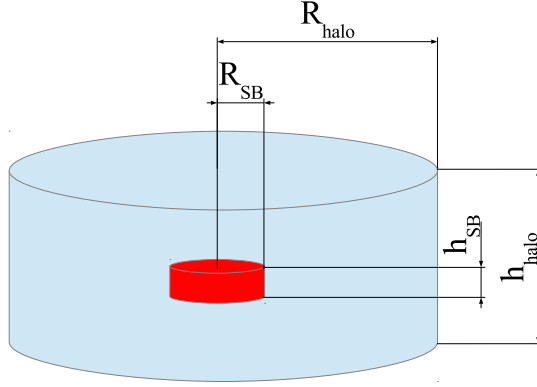


Figure 3.1: The geometry of the model. The red cylinder represents a starburst region (SB) with radius R_{SB} and height h_{SB} surrounded by a synchrotron halo with radius R_{halo} and height h_{halo} (blue).

3.2 Numerical modelling of radio emission

In order to model radio emission from galaxies we developed software that enabled us to solve the radiative transfer equation in 3D taking into account projection effects. We introduced components of galaxies as a starburst region and a halo, which were approximated by cylinders decomposed into a 3D grid (Figure 3.1). In each grid cell within a given component we set parameters of synchrotron- and thermal-emitting gas (synchrotron intensity, synchrotron spectral index, density, and temperature of ionized gas). As synchrotron-self absorption can be only important in compact objects with high brightness temperature of above 10^{10} K, we neglected synchrotron absorption coefficient in our modelling. Once galaxy was rotated by inclination angle, we solved the radiative transfer equation along each line of sight, distinguishing two solutions for the radiative transfer equation in the cell along the path through the galaxy towards the observer. Depending on the content of the cell with index n and the preceding cell with index $n - 1$, they are given by:

$$S_n = \begin{cases} S_{n-1} e^{-\tau_n} + (2kT_e \nu^2 c^{-2} + B_n \tau_n^{-1}) (1 - e^{-\tau_n}) \Omega \\ S_{n-1} + B_n \Omega \end{cases} \quad (3.1)$$

where

$$\tau_n = 8.235 \times 10^{-2} \left(\frac{T_e}{\text{K}} \right)^{-1.35} \left(\frac{\nu}{\text{GHz}} \right)^{-2.1} \left(\frac{EM_n}{\text{pc cm}^{-6}} \right) \quad (3.2)$$

is the optical depth of ionized gas in the cell with index n , T_e is the thermal electron temperature, $EM_n = sN_{e,n}^2$ is the emission measure of the cell, $N_{e,n}$ is the thermal electron density, and s is the size of the cell. The synchrotron intensity in the cell with index n is given by B_n , and Ω is the cell's solid angle.

The first solution in Equation 3.1 corresponds to the cell filled with well-mixed synchrotron and thermal gas. The ionized gas in the cell with the index n due to free-free absorption attenuates the radio emission from the preceding cell S_{n-1} by a factor $e^{-\tau_n}$. Thus, S_n is a sum of the absorbed radio emission from the cell with the index $n - 1$ and the

radio emission from the cell with the index n coming from thermal and synchrotron gas reduced by free-free absorption. The other solution in Equation 3.1 assumes no ionized gas in the cell with the index n , and thus the radio emission is a sum of the contribution from the previous cell and the synchrotron emission from the cell with the index n . This solution applies for the regions in the galactic halo where usually pure synchrotron emission is expected. We obtained synthetic maps of radio emission (total, synchrotron, and thermal) by solving the radiation transfer for all cells in the grid for particular viewing angles and different frequencies. In order to construct the modelled global spectrum, each map was used to integrate flux densities of total, synchrotron and thermal radio emissions. The procedure was repeated for each model with different parameters of synchrotron- and thermal-emitting gas and values of viewing angle. Comparing the resulting global spectra for various models, we were able to investigate significance of model parameters and their influence on the shape of global spectra of galaxies.

More about the code can be found in Appendix E, where we also present some tests of its stability and precision.

3.3 Radio spectra of galaxies

3.3.1 Density of ionized gas and projection effects

In our modelling, we started by analysing the impact of thermal gas density on galaxy spectra. For the purpose of modelling presented in this chapter we assumed the cell size of 5 pc with the total number of grid points of 3.3×10^7 . The starburst region in our model was approximated by a cylinder with radius $R_{SB} = 200$ pc and height $h_{SB} = 100$ pc. A similar model representing the starburst region in M82 as a cylinder was also proposed by Yoast-Hull et al. (2013). We assumed the distance to the modelled object as 3.52 Mpc, corresponding to that for M82 (Jacobs 2009). The starburst region was then regarded as a well-mixed uniform thermal and synchrotron plasma. In this model, we did not include synchrotron emissions from the galactic halo. Other parameters assumed in this model are summarized in Table 3.1. The thermal gas is described by the uniform thermal electron density N_e and temperature of 10^4 K. The synchrotron intensity B_n in the starburst region is approximated by $A_{nc} \nu^{\alpha_{nt}}$, where A_{nc} is scale factor and α_{nt} is the synchrotron spectral index. The parameter b denotes the ratio of the volumes of thermal to synchrotron emitting region. The $b = 1.0$ corresponds to a region radiating both thermally and non-thermally over the entire volume. We solved the radiative transfer equation for a number of different thermal electron densities (N_e) and frequencies, keeping the same thermal fraction of 10% at 1.4 GHz by compensating the synchrotron emission via modification of A_{nc} (see Table 3.1).

The results of modelling of the starburst region seen as an edge-on galaxy ($i = 90^\circ$) for N_e in the range $30 - 180 \text{ cm}^{-3}$ are presented in Figure 3.2 (left panel). The integrated spectra of galaxies show a turnover at higher frequencies for greater density of ionized gas. The location of spectral turnover is proportional to the emission measure of ionized gas. The modelled global spectra also show turnover in the range of frequencies from about 0.4 to about 2 GHz, which corresponds to the range of emission measure from $9 \times 10^4 \text{ pc cm}^{-6}$

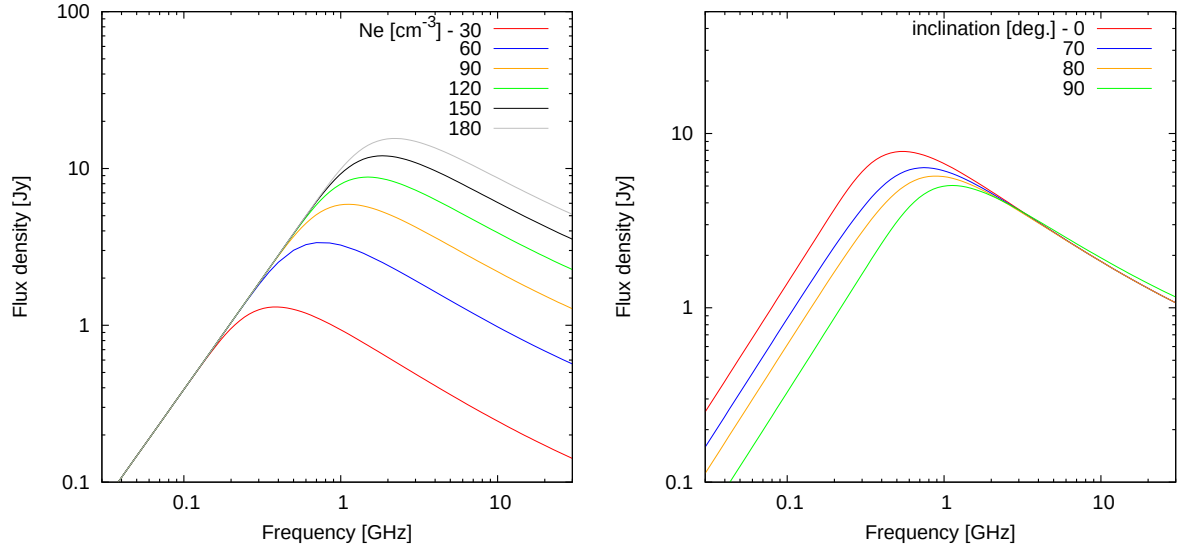


Figure 3.2: (Left) Effect of the thermal electron density (determined by the EM) on low-frequency spectra of starburst galaxies seen edge-on. The thermal- and synchrotron-emitting gases are fully mixed with a constant 10% thermal fraction at 1.4 GHz (to be compared with the analytical model of Condon 1992). (Right) Similar model applied to a galaxy seen at a different viewing angle with $N_e = 80 \text{ cm}^{-3}$.

Table 3.1: Model parameters of starburst region in M82 with different density of thermal gas N_e . The only one value of parameter in the central row of a column means that all values of parameter are the same in each row of that column.

b	i	N_e	A_{nc}	f_T	α_{nt}
	deg.	cm^{-3}	10^{13} Jy/sr	1.4 GHz	
1.0	90	30	0.19	10%	-0.7
		60	0.79		
		90	1.79		
		120	3.18		
		150	4.98		
		180	7.17		

to $3.2 \times 10^6 \text{ pccm}^{-6}$. Our 3D model of a starburst region well reproduces the results of the analytical 1D spectral model of Condon (1992), which also assumes the well-mixed thermal and synchrotron plasma.

We extended the Condon modelling and investigated the influence of projection effects on the shape of galaxy spectra by modelling the starburst region as viewed at different angles. Our model was adjusted to reproduce the modelled flux density at 1.4 GHz as comparable to the observed flux density of M82 at this frequency (Adebahr et al. 2013). We set the thermal gas density and the scale factor of the synchrotron emission (A_{nc}) so as to keep thermal fraction at the level of 10% (Table 3.2).

Table 3.2: Model parameters of starburst region viewed at different inclination angles.

b	i	N_e	A_{nc}	f_T	α_{nt}
	deg.	cm^{-3}	10^{13} Jy/sr	1.4 GHz	
1.0	0	80	1.5	10%	-0.7
	70				
	80				
	90				

The modelled global spectra of starburst region seen at different viewing angle (inclination) of 0° , 70° , 80° , and 90° are shown in Figure 3.2 (right panel). For less inclined galaxies we obtained a stronger emission due to lower free-free absorption. Such galaxies show spectral turnovers at lower frequencies. The shape of global spectrum of galaxies is less affected by changing inclination angle in the range from 0° to 70° than by a small increase of viewing angle above 70° for a high-inclined galactic disk. For more inclined galaxies spectral turnovers appear at higher frequencies, which results from increase of path length through ionized gas corresponding to the emission measure of $2.5 \times 10^6 \text{ pc cm}^{-6}$ for edge-on objects. Much less emission measure is for face-on galaxies of $6.4 \times 10^5 \text{ pc cm}^{-6}$.

3.3.2 Role of synchrotron halo, thermal emission and projection effects

Synchrotron halos are observed in starburst galaxies like M82 (Adebahr et al. 2013) and Arp 220 (Varenius et al. 2016), particularly at low frequencies. Such a synchrotron halo can build up when several starbursting periods occurred in a galaxy, and CREs were transported in galactic wind flow together with gas (advection). Low-energy CREs observed at low frequencies are less affected by energy loss mechanisms and can travel for higher distances from the galactic mid-plane than CREs observed at higher frequencies (Section 1.1). Since no synchrotron halo was included in the model of Condon (1992), we constructed another model involving synchrotron halo which surrounded a starburst region of the same physical size as the model considered in Section 3.3.1. In our modelling, synchrotron halo was approximated by $R_{\text{halo}} = 500 \text{ pc}$ and $h_{\text{halo}} = 1 \text{ kpc}$ basing on 0.33 and 1.4 GHz height scales determined for M82 in the southern part of the galaxy, which has less complex structure than the northern part (Adebahr et al. 2013). We assumed the same initial density of ionized gas of 30 cm^{-3} in the starburst region following the previous model presented in Table 3.1.

Table 3.3: Model parameters of starburst region with different density of thermal gas N_e surrounded by synchrotron halo.

b	i deg.	N_e cm^{-3}	A_{nc} 10^{13} Jy/sr	A_{nh} 10^{11} Jy/sr	f_T 1.4 GHz	α_{nt}
0.1	90	30	0.18	0.22	10%	-0.7
		60	0.67	0.83		
		90	1.36	1.69		
		120	2.13	2.66		
		150	2.88	3.61		
		180	3.57	4.46		

We solved the radiative transfer equation for a number of different thermal gas densities and frequencies. In each case, we set the thermal fraction to 10% at 1.4 GHz by adjusting synchrotron emission in the starburst region and in the halo with the use of parameters A_{nc} and A_{nh} , respectively (Table 3.3). We set the value of parameter $b = 0.1$, which means that the central part of galaxy, containing both the thermal and synchrotron gas from the starburst region, accounts for 10% of the entire volume of synchrotron halo.

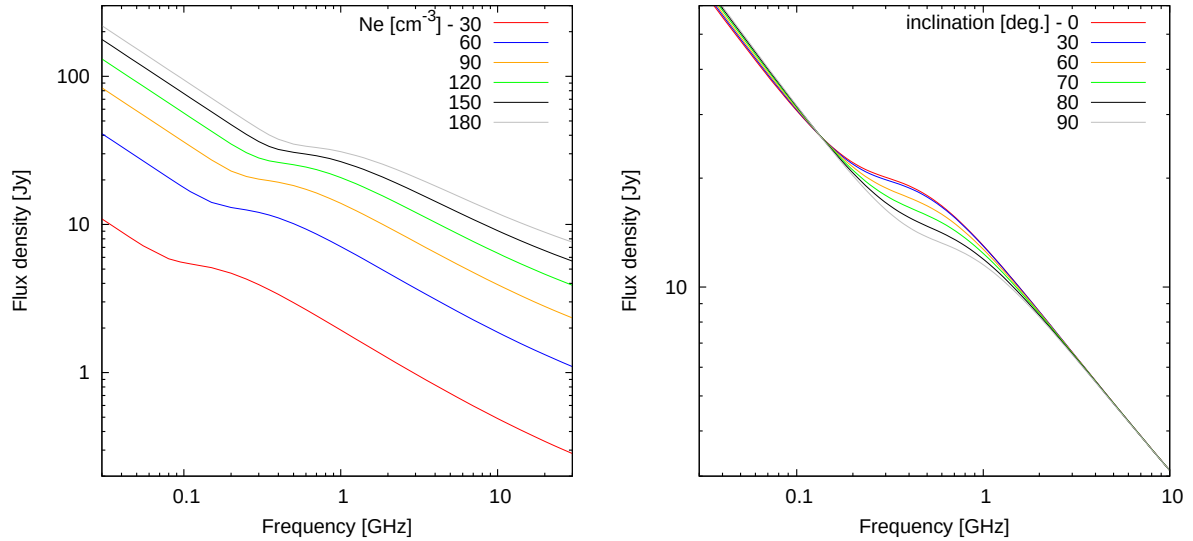


Figure 3.3: (Left) Effect of the thermal electron density (determined by the EM) on low-frequency spectra of starburst region surrounded by synchrotron halo. (Right) A similar model applied to a galaxy, but with a lower 5% thermal fraction seen at a different viewing angle.

The modelled spectra are shown in Figure 3.3 (left panel). As in the model of Condon, the spectral turnovers appear at greater frequencies for higher densities of ionized gas densities. Unlike the integrated spectra of starburst region in the previous model (Figure 3.2, left panel), radio emission from the synchrotron halo of the current model causes the integrated spectrum to raise below the turnover frequency. Such spectral features have been actually observed in the integrated spectra of starburst galaxies Arp 220 (Varenius et al. 2016) and (U)LIRGs (Clemens et al. 2010), and cannot be accounted for in the simple model of Condon (1992).

In order to investigate the influence of projection effects on the integrated spectra of galaxies with synchrotron halos, we constructed also a model of starburst region with synchrotron halo, but with a much lower thermal emission, assuming its value at the level of 5% at 1.4 GHz for edge-on object. The lower value of thermal fraction was chosen to investigate whether similar effects on the integrated spectra can be expected as for galaxies with thermal fraction of 10%. We solved radiative transfer equation for different viewing angles and frequencies without assumption of constant thermal fraction for all cases, as summarized in Table 3.4.

Table 3.4: Model parameters of starburst region surrounded by synchrotron halo seen at different viewing angles.

b	i deg.	N_e cm^{-3}	A_{nc} 10^{13} Jy/sr	A_{nh} 10^{11} Jy/sr	f_T 1.4 GHz	α_{nt}
0.1	0	80	1.5	2.06	5.40%	-0.7
	30				5.34%	
	60				5.28%	
	70				5.21%	
	80				5.10%	
	90				5.0%	

The shape of the modelled integrated spectrum (Figure 3.3, right panel) changes in the

frequency range from 0.15 to 2 GHz due to different amounts of absorption in the starburst region seen at different viewing angles. This effect causes also a small increase of thermal fraction at 1.4 GHz for the less inclined galaxies (Table 3.4). Both below and above the range of frequencies the modelled integrated spectra overlap. A spectral turnover appears at higher frequencies for higher viewing angles, similarly to the integrated spectra of a starburst region with no synchrotron halo (Figure 3.2, right panel). The modelled integrated spectra above 2 GHz are not affected by absorption, since all radio emission arises from optically thin gas. Below 0.15 GHz the integrated spectrum is dominated by increased flux density of synchrotron halo, and as the starburst region is fully absorbed by thermal gas, dependence on viewing angle towards low frequencies is negligible.

3.3.3 Role of size and intensity of synchrotron halo

The models mentioned above show the integrated spectra that reveal a decrease of flux density below turnovers or a raise of global spectrum towards low frequencies due to increased emission from a synchrotron halo. In order to analyse the effect of relative volumes of starburst regions and synchrotron halos we carried out another modelling taking into account various values of parameter b . We modelled radio emission from a galaxy having the thermal fraction of 10% kept constant at 1.4 GHz. In our modelling, we achieved a constant level of the thermal fraction by decreasing N_e with greater volume of starburst region with respect to the synchrotron halo, solving the radiative transfer equation for one inclination angle (edge-on) and for different values of parameter b , as summarized in Table 3.5.

Table 3.5: Model parameters of starburst region with different b ratio of the volumes of thermal to synchrotron emitting region (halo).

b	$i.$ deg.	N_e cm^{-3}	A_{nc} 10^{13} Jy/sr	A_{nh} 10^{13} Jy/sr	f_T 1.4 GHz	α_{nt}
0.1		80.7				
0.6		18.6				
0.8		13.8				
0.9		12.0				
0.95	90	11.4	1.13	0.014	10%	-0.7
0.975		11.0				
0.99		10.8				
0.9995		10.1				
1.0		10.0				

The modelled global spectra depend strongly on the value of parameter b (Figure 3.4, left panel). For higher values of parameter b , the integrated galactic spectra are more dominated by radiation from well-mixed synchrotron and thermal gas, as in the case of starburst regions. Initially, starting with low values of b , the global spectra at frequencies below the spectral turnover follow the power-law synchrotron spectrum of the galactic halo.

We also investigated the impact of intensity of synchrotron halo on the integrated spectra of galaxies, using the same model as above and keeping the constant value of parameter $b = 0.1$. In our modelling, the radiative transfer equation was solved for the

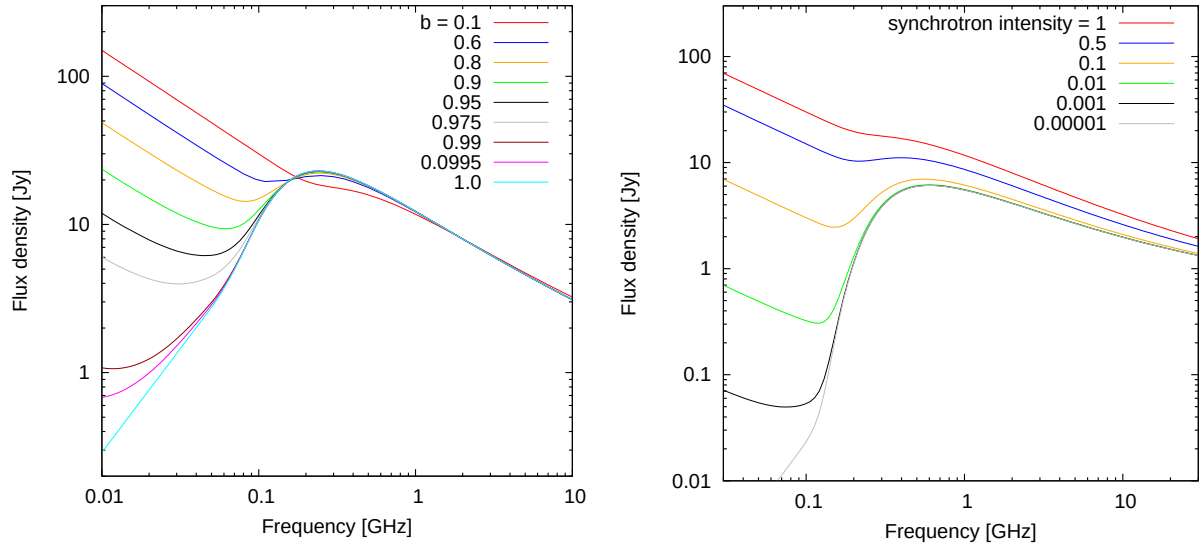


Figure 3.4: (Left) Model of a starburst galaxy with a synchrotron halo of varying size, as measured by the ratio b (see text for details). The thermal fraction of the disk emission is assumed to be 10% at 1.4 GHz for all models. (Right) Similar model with the same synchrotron halo of $b = 0.1$ but different synchrotron intensity, and varying thermal fraction.

case of edge-on galaxy and for different values of intensity of synchrotron halo by changing values of parameter A_{nh} , as presented in Table 3.6.

Table 3.6: Model parameters of starburst region surrounded by synchrotron halo with different intensity.

b	inc. deg.	N_e cm^{-3}	A_{nc} 10^{13} Jy/sr	A_{nh} 10^{11} Jy/sr	f_T 1.4 GHz	α_{nt}
0.1	90	80.7	1.13	1.0	10%	-0.7
				0.5	16.3%	
				0.1	18.35%	
				0.01	20.02%	
				0.001	20.20%	
				0.00001	20.22%	

Our modelling shows that even keeping b constant, the modelled global spectra can still be easily modified by the level of synchrotron intensity in the halo (Figure 3.4, right panel). For lower values of intensity of synchrotron halo, radio emission from the starburst region becomes more important and dominates the global spectrum of galaxy. For higher intensity of emission from the synchrotron halo, the global spectra manifest a raise at frequencies below spectral turnovers. This can suggest that sufficiently high intensity of synchrotron halo can produce a power-law global spectrum of galaxies without any evidence of free-free absorption. Therefore, changes in halo intensity can modify the effect of the halo size on the galactic spectrum and hence introduces the degeneracy in the model fitting, which can be eliminated e.g. by exact knowledge of the halo morphology.

3.3.4 Role of synchrotron spectral index

In our modelling of integrated radio spectra of galaxies we assumed a constant value of the synchrotron spectral index $\alpha_{nt} = -0.7$ both in the starburst region and the synchrotron

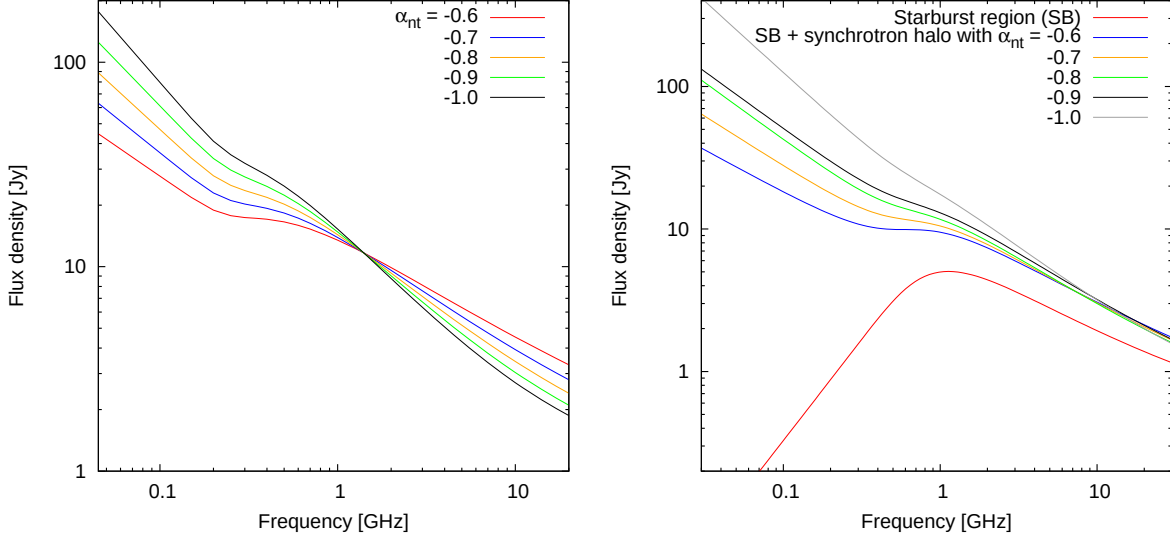


Figure 3.5: (Left) Model of starburst galaxy with synchrotron halo for different values of synchrotron spectral index. (Right) Similar model for different values of synchrotron spectral index of the halo.

halo. Multi-frequency studies of M 82 (Adebahr et al. 2013) in the frequency range from 0.3 to 8.4 GHz showed that the observed radio spectrum of the starburst core has the spectral index $\alpha_c = -0.62$, similar to the spectral index of the entire galaxy ($\alpha_t = -0.67$). These values were obtained by fitting a spectral model involving foreground ionized gas that causes free-free absorption. The authors determined also the spectral index of synchrotron halo, which is $\alpha_h = -1.20$. On the other hand, the averaged synchrotron spectral index based on the integrated flux density of 74 galaxies found by Niklas et al. (1997b) is about -0.83 . The value of mean $\alpha_{nt} = -0.78$ of local spectral indices in the regions with a high thermal fraction above 10% was obtained by Basu et al. (2012) basing on studies of 4 spiral galaxies. The value of synchrotron spectral index of -0.7 in our modelling was chosen as a compromise between the typical spiral galaxies and starburst regions and the spectral index of M 82, following Adebahr et al. (2013).

We investigated the impact of synchrotron spectral index on the shape of integrated spectra of galaxies by solving the radiative transfer equation for different α_{nt} . For this purpose we adjusted the model of starburst region surrounded by a synchrotron halo with density of thermal gas $N_e = 90 \text{ cm}^{-3}$ (see Table 3.3). In our modelling, we kept the constant value of thermal fraction of 10% at 1.4 GHz. The parameters assumed during modelling are presented in Table 3.7.

Table 3.7: Model parameters of starburst region surrounded by synchrotron halo for different synchrotron spectral index α_{nt} . The values of α_{nt} were the same for the starburst region and the halo.

b	inc. dec	N_e cm^{-3}	A_{nc} 10^{13}	A_{nh} 10^{11}	f_T 1.4 GHz	α_{nt}
			0.17			-0.6
			1.4			-0.7
0.1	90	90	11.3	1.69	10%	-0.8
			91.7			-0.9
			753.0			-1.0

The modelled global spectra shown in Figure 3.5 (left panel) are steeper for lower values of synchrotron spectral index and moreover the spectral turnovers are less pronounced than for the limit case of $\alpha_{nt} = -0.6$.

Furthermore, we modelled the effect of changing only of the spectral index of synchrotron halo on the integrated spectra of galaxies. In our modelling we, modified values of spectral index in the synchrotron halo, while $\alpha_{nt} = -0.7$ in the starburst region was kept constant. The modelled global spectra for the synchrotron spectral index of halo -0.6 , -0.7 , -0.8 , -0.9 , and -1.0 are presented in Figure 3.5 (right panel). For steeper synchrotron spectra of halo, there is also a steeper increase of radio emission in the integrated spectra of galaxies at frequencies below the spectral turnover.

3.4 Conclusions

I developed and used a simple model of starburst galaxy to investigate the significance of different physical parameters of thermal- and synchrotron-emitting gas, as well as of projection effects, on the shape of integrated spectra of galaxies. My 3D numerical modelling of radio emission led us to the following conclusions.

- 3D model of a starburst region containing well-mixed uniform thermal and synchrotron gas well reproduces the results of the analytical simple 1D model of radio emission by Condon (1992). For greater density of ionized gas in the starburst region, the modelled spectra demonstrate turnovers at higher frequencies (Figure 3.2, left panel). Contrary to the analytical model of Condon (1992), in my modelling it was possible to predict emission and spectra of galaxies seen at different viewing angles. I found that less inclined objects are stronger radio emitters and have spectral turnovers at lower frequencies (Figure 3.2, right panel).
- Because the spectral model of Condon (1992) did not take into account synchrotron halos observed in starburst galaxies, I constructed another model of starburst galaxy with a synchrotron halo surrounding the starburst region. My modelling have demonstrated that unlike the integrated spectra of the starburst region only, synchrotron emission from the halo causes a raise in the integrated spectrum below the turnover frequency (Figure 3.3). The larger synchrotron halo the less pronounced spectral turnovers are observed (Figure 3.4, left panel). The spectral features predicted by this model were observed so far in the integrated spectra of starburst galaxies Arp 220 (Varenius et al. 2016) and (U)LIRGs (Clemens et al. 2010). Moreover, the turnover frequency in the integrated spectra is different for objects with different viewing angle.
- Furthermore, the model predicts a degeneracy between the halo size and the halo synchrotron intensity such that as the halo is larger, a decrease in synchrotron intensity allow a similar spectral shape (Figure 3.4). Therefore, details of halo morphology are needed to constrain the model.
- I investigated also the impact of the synchrotron spectral index α_{nt} on the shape

of integrated spectra of galaxies. For steeper synchrotron spectra of halo, the integrated spectra of galaxies show less pronounced spectral turnovers (Figure 3.5).

In general, the local spectra in galaxies have various values of synchrotron spectral index in different galactic regions, as it can be seen in the spectral index map of NGC 6946 (Figure 2.9) and typically also in other galaxies. This is a result of different CREs energy loss mechanisms and propagation effects of CREs, which are directly related to the observed radio emission. Particularly synchrotron, inverse-Compton, and ionisation losses, which affect population of CREs, can lead to curving of local synchrotron spectra. Moreover, the structure and composition of ISM in galaxies are much more complex than those in the presented modelling, which assumes a homogeneous distribution of ionized gas. Dense HII regions in the galactic nucleus and in the spiral arms clearly contradict these assumptions and can cause locally higher thermal emission and stronger free-free absorption effects.

Therefore, it is not possible to fully interpret the integrated spectra of galaxies without detailed information about the distribution of thermal- and synchrotron-emitting gas throughout the galaxy disk. Our simple model enabled us to show that various parameters can have a very similar effect on the shape of integrated spectra. Moreover, determining which physical parameters are responsible for the shape of the integrated spectrum can be obscured by projection effects.

The limited character of the mentioned models raises the need to build advanced models that would allow to draw general conclusions about the origin of curved spectra in the observed nearby galaxies. This requires more detailed data on the distribution of the thermal and synchrotron emitting medium across the galaxy. Furthermore, optical and multi-frequency radio data, including those obtained at low frequencies, will be needed for the models' verification.

CHAPTER 4

Three-dimensional modelling of low-frequency radio continuum spectra of M 51-like and M 82-like galaxies

4.1 Introduction

My LOFAR HBA observations of the nearby star-forming galaxy NGC 6946 (see Chapter 2) showed that the integrated spectrum revealed no effects of free-free absorption at low frequencies down to 144 MHz. Similarly, the earlier LOFAR data of another star-forming galaxy, M 51, indicated that also in this case the spectrum could be described by a single power-law (Mulcahy et al. 2014). Contrary to that, both NGC 6946 and M 51 manifest absorption of synchrotron emission due to ionized gas in some local regions of their disks associated with the galactic nucleus and giant HII complexes.

It is also known that free-free absorption is necessary to account for the observed spectra of local regions in the centres of some galaxies, including Sgr A Complex in the Milky Way (Pedlar et al. 1989, Roy & Pramesh Rao 2006). Effects of this kind can be also found in the centre of M 82 at 408 MHz (Wills et al. 1997) and at 150 MHz (Varenius et al. 2015). In this starburst galaxy, absorption effects were proposed to explain the integrated spectrum of M 82, which reveals a weak flattening at frequencies below 300 MHz (Condon 1992, Yoast-Hull et al. 2013, Lacki 2013, Adebahr et al. 2013). Interestingly, several objects in a sample of luminous and ultra-luminous IRAS galaxies studied by Clemens et al. (2010) showed radio spectra with two components having turnovers at different frequencies. Such spectra can indicate that the observed radio emission originates from regions with very different properties, which trace different evolutionary stages of a starburst.

The presented above observational findings, make evident that a proper interpretation of the global and local spectra requires advanced modelling of galaxy radio emission. Such modelling should involve detailed information on distributions of ionized gas and synchrotron-emitting plasma, and on CREs transport. Here I present my attempt to this task by applying the 3D numerical model (Chapter 3) to reproduce radio emission of galaxies at various frequencies. Looking through the available literature, I selected two suitable candidates for modelling, which had been extensively studied in a wide range of frequencies. In the case of nearby star-forming galaxies, I found that M 51 was more explored than NGC 6946, including studies of distribution of ionized gas (e.g. Greenawalt et al. 1998, Gutiérrez & Beckman 2010), so I selected M 51. For a case study

of starburst galaxy, I considered the intensively studied M82. This galaxy was also observed during the commissioning phase of the 42 element Allen Telescope Array (ATA) in the frequency range from 1.0 GHz to 7.0 GHz with a spacing of 0.1 GHz, which provided its unprecedented broadband continuous radio spectrum (Williams & Bower 2010).

In this Chapter in Section 4.2, I discuss the influence of the volume filling factor of ionized gas on the modelled shape of galactic spectra. I use spatially revolved information on the observed radio emission at different frequencies to constrain my model parameters for M51 and M82 (Sections 4.3.1 and 4.4.1). In my modelling, I produce synthetic radio emission maps for various galaxy inclinations and at different frequencies. In each map, I integrate flux density, which allow me to reconstruct and interpret the integrated spectra of M51 and M82 (Section 4.3.2 and 4.4.2). In Section 4.5, I discuss processes leading to flattening of synchrotron spectrum. Finally in Section 4.6, I provide my conclusions.

4.2 Influence of volume filling factor of ionized gas on radio spectra

In Chapter 3, we discussed a simple modelling of galactic radio emission assuming uniform distribution of ionized gas. However, the Galactic ionized gas traced by H α emission show a great variety of structures, such as clouds, filaments, shells, and voids, which can be produced by supernova explosions, shocks, and turbulences in the ISM. Moreover, the HII regions in the galactic disk are surrounded by the diffuse ionized gas (DIG) with a scale height of about 1 kpc (Reynolds 1991). In general, both HII regions and DIG have a form of clumps or clouds distributed with the volume filling factor f_V (e.g. Berkhuijsen & Müller 2008), describing the fraction of the galactic volume occupied by clouds (see Appendix B for more details on ISM properties).

In order to investigate the role of f_V on the galactic spectra, we modelled the radio emission from the volume of 1 kpc³ located in the galaxy at a distance of 1 Mpc. We assumed the same clump size as for the cell size, that is 5 pc. This gave 8×10^6 cells in the grid. The synchrotron-emitting gas was set uniformly within the volume, while the ionized gas was distributed randomly according to f_V . We solved the radiative transfer equation for different values of f_V in the range from 1.0 to 0.001, keeping the same thermal fraction of 10% at 1.4 GHz by changing the density of thermal gas within clumps in the range from 10 to 300 cm⁻³, respectively.

We found that the f_V value does not affect the frequency of spectral turnover due to thermal absorption (see Figure 4.1, left panel). For higher f_V , free-free absorption of the synchrotron emission is more significant, since there are less foreground cells emitting exclusively synchrotron emission. Therefore, the global spectra show more distinct decrease of radio emission at frequencies below turnovers. In the extreme cases of $f_V \approx 1$ we get a smooth distribution of thermal absorption, which corresponds to the Condon model (Figure 3.2) and the model with galactic halo with a high value of parameter b (Figure 3.4, left panel).

In our modelling, different f_V results in different distribution of emission measure along the line of sights. However, in each case the overall thermal emission from the

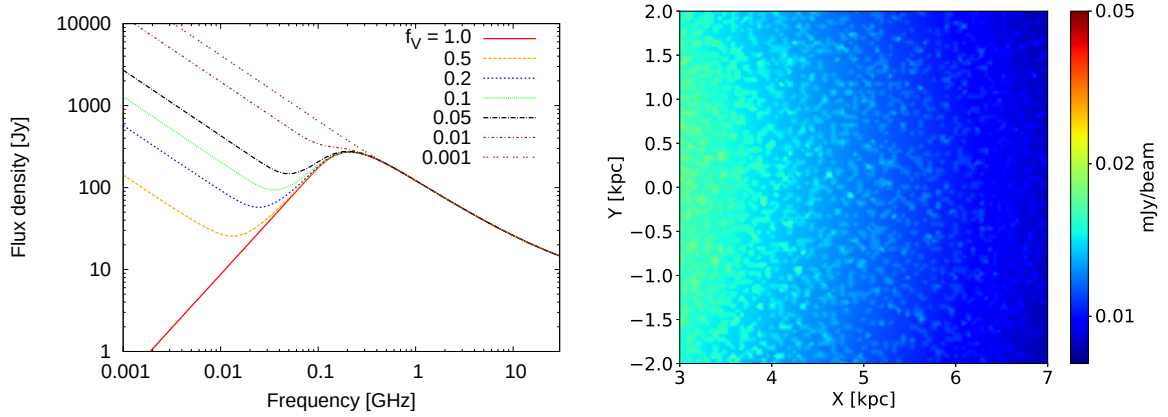


Figure 4.1: (Left) The influence of different volume filling factors f_V of ionized gas on global spectra from the source (volume of 1 kpc^3) at distance of 1 Mpc. The spectra correspond to f_V in the range from 1.0 (uniform gas) to 0.001, while the density of thermal gas within clumps was changed in the range from 10 to 300 cm^{-3} , respectively, keeping the thermal fraction of 10% at 1.4 GHz. (Right) The synthetic radio emission of a galactic region at 1.4 GHz illustrating clumpy medium with $f_V = 0.2$.

entire volume is the same at frequencies above turnover. This is visible in identical high frequency spectra regardless of the model f_V . The shape of low-frequency spectra (below the turnover) can be used as an independent constraint in modelling of filamentary structure of the ISM within galaxies. Example of model distributions obtained for clumpy medium with $f_V = 0.2$ is presented in Figure 4.1 (right panel). Additionally, we introduced in this model a density gradient of thermal and synchrotron medium to reproduce the transition from the emission in the galactic disc to the halo. However, the resulting filamentary structure of the modelled emission is well visible. Such modelling of the entire galaxies with emitting gas described by f_V requires much higher resolution of the grid, and computing resources, and is beyond the scope of this work. Therefore, in the following sections, we present models assuming smooth distributions of both the synchrotron- and thermal-emitting gas with $f_V = 1$.

4.3 Numerical modelling of M 51-like galaxies

4.3.1 Model parameters for M 51-like galaxies

We modelled radio emission of M 51 as a case study of non-starbursting galaxy visible at low inclination angle ($i \approx 20^\circ$) using numerical methods including solving of radiative transfer equation (Equation 3.1) as described in Chapter 3. However, a simple cylinder approximation was replaced by a more complex morphology of the modelled galaxy, which is discussed in this Section. In our modelling we set the cell size of 50 pc with the total number of grid points of 2.7×10^8 .

We assumed that the thermal gas in M 51 has a similar distribution as in the Milky Way and $f_V = 1$. Like in the model of ionized gas for the Galaxy proposed by Lyne et al. (1985), we represented thermal emitting gas by two vertical components: the thin and thick disks. The distribution of thermal electron density (N_e) was approximated by

exponential functions with scale heights of 0.1 kpc for the thin disk and 1 kpc for the thick disk, following modelling of the ISM structure in the Milky Way by Cordes (2004). The radial dependency of N_e was introduced as inner and outer exponential disks. We used the H α -derived emission measure map by Greenawalt et al. (1998) to determine a radial profile for the inner disk. In the outer disk we assumed a radial scale length of 10 kpc, following Gutiérrez & Beckman (2010). The density of ionized gas in the plane of this component is approximated as 0.02 cm^{-3} , a typical value in the Milky Way models (Ferrière 2001). Accordingly, the 3D distribution of thermal gas was derived in the following form:

$$N_e(r, z) = A^a \sqrt{\frac{EM(r)}{0.1 \text{ kpc}}} \exp\left(\frac{-|z|}{0.1 \text{ kpc}}\right) + 0.02 \exp\left(\frac{-r}{10 \text{ kpc}}\right) \times \exp\left(\frac{-|z|}{1 \text{ kpc}}\right) \quad (4.1)$$

where A^a denotes a constant with superscript a . We use the superscript a to denote values in this and following equation that refer to the modelling of M51-like galaxies. We set the value of A^a so as to acquire the integrated thermal radio emission at 14.7 GHz corresponding to the thermal fraction of 28% estimated by Klein et al. (1984) at the same frequency. Equation 4.1 was then used to calculate the emission measure EM_n in each cell of the thermal component.

The synchrotron emission of the modelled galaxy was derived after taking into account a few observational findings given below. The multi-frequency observations of M51 revealed that the scale lengths of mean radial profiles of radio emission at 151 MHz of the inner and outer disks are longer than at 1400 MHz (Mulcahy et al. 2014). Moreover, the local spectra in the centre of M51 are nearly flat and become steeper towards the edge of galaxy, due to ageing of CREs by synchrotron and IC energy losses. LOFAR observations of M51 and numerical simulations provided evidences for diffusion of CREs from the star-forming regions into the inter-arm regions, and the outer parts of the galaxy. We modelled the unabsorbed synchrotron intensity $B_n(r, z)$ as two vertical disks (thin and thick, see explanations in Appendix C) with a radial variation that is given by the following four different continuous functions:

$$B_n(r, z) = \begin{cases} C^a \exp(-0.5/R_1^a) [\exp(-|z|/Z_1^a) + \exp(-|z|/Z_2^a)] \\ C^a \exp(-r/R_1^a) [\exp(-|z|/Z_1^a) + \exp(-|z|/Z_2^a)] \\ C^a \exp(-r/R_2^a) \left[\frac{\exp(-1.7/R_1^a)}{\exp(-1.7/R_2^a)} \right] [\exp(-|z|/Z_1^a) + \exp(-|z|/Z_2^a)] \\ C^a \exp(-r/R_3^a) \left[\frac{\exp(-1.7/R_1^a)}{\exp(-1.7/R_2^a)} \right] \left[\frac{\exp(-10/R_2^a)}{\exp(-10/R_3^a)} \right] [\exp(-|z|/Z_1^a) + \exp(-|z|/Z_2^a)] \end{cases} \quad (4.2)$$

where the consecutive equations describe four different sections of radial distance from the galactic centre: $r < 0.5 \text{ kpc}$, $0.5 \leq r < 1.7 \text{ kpc}$, $1.7 \leq r < 10 \text{ kpc}$, and $10 \leq r \leq 16 \text{ kpc}$ respectively. The parameter C^a is a scale factor and R_1^a , R_2^a , R_3^a are scale lengths of corresponding sections described by exponential radial profiles of synchrotron emission basing on the radial profile of radio emission at 151 MHz obtained by Mulcahy et al. (2014). In the first section ($r < 0.5 \text{ kpc}$), we kept radial dependence of synchrotron emissions con-

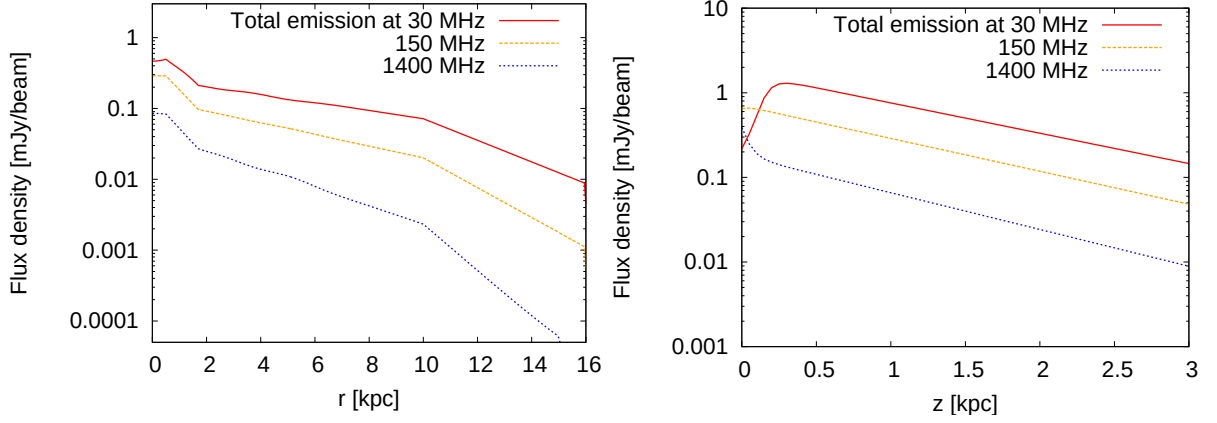


Figure 4.2: (Left) Modelled radial profiles of total radio emission of a M51-like galaxy seen face-on at 30, 150, and 1400 MHz. (Right) Model vertical profiles of total radio emission of a M51-like galaxy seen edge-on at 30, 150, and 1400 MHz.

stant, because of the central part of M51 was not resolved in the observational profile at 151 MHz (Mulcahy et al. 2014). Moreover, radial dependence in the centre would lead to a strong centrally concentrated source as a consequence of the assumed exponential function. We believe that a such strong source in the centre should not be expected due to diffusion of CREs. The vertical dependence of synchrotron emission is described by two components: thin and thick exponential disks with scale heights Z_1^a and Z_2^a , respectively. The frequency dependence of modelled synchrotron intensity $B_n(r, z)$ is described by a scale factor $C^a = f(\nu)$. Initially, we adopted $f(\nu)$ in the form of a power-law function ($\propto \nu^{\alpha_{nt}}$), similarly as in the 1D analytical models of synchrotron spectra (e.g. Section 3.3.1).

To reconstruct the radial profile of the spectral index of M51 between 151 and 1400 MHz (Mulcahy et al. 2014), the scale heights and lengths of synchrotron radio emission profiles have to be frequency-dependent. In my modelling of galaxies in Chapter 3, I analysed influence of the extent and intensity of a synchrotron halo on the integrated spectra of galaxies. For simplicity sake, I assumed that the size of the synchrotron halo is the same at all frequencies. However, low-frequency observations of both nearby star-forming galaxies (e.g. NGC 6946: Chapter 2, M51: Mulcahy et al. 2014) and starburst galaxies (e.g. M82: Adebahr et al. 2013) reveal a more extended radio emission than at higher frequencies (see e.g. the determined scale lengths of NGC 6946). Various CREs propagation mechanisms can cause such a frequency dependence (Mulcahy et al. 2014, Krause et al. 2018). We adopted the following power-law functions: $R_2^a(\nu), R_3^a(\nu) \propto (\nu/\nu_1)^{D_a}$ and $Z_1^a, Z_2^a \propto (\nu/\nu_2)^{E_a}$. The scale lengths R_1^a , R_2^a , and R_3^a at $\nu_1 = 0.15$ GHz were estimated as: 1.1 kpc, 5.3 kpc, and 2.1 kpc, following radial profiles presented by Mulcahy et al. (2014). We approximated the values of the scale heights Z_1^a and Z_2^a at $\nu_2 = 4.85$ GHz as 0.3 kpc and 1.8 kpc, which are typical scale heights of edge-on galaxies (Krause et al. 2018). Moreover, we noticed that a better fit of the integrated spectrum was achieved when the initial functional form of C^a was replaced by a third-degree polynomial: $\log C^a(\nu) = C_0^a + C_1^a \log \nu + C_2^a \log^2 \nu + C_3^a \log^3 \nu$.

In order to model the integrated spectrum of M51, we assumed some initial values of the parameters describing the synchrotron emission R_1^a , R_2^a , R_3^a , Z_1^a , Z_2^a , the frequency-

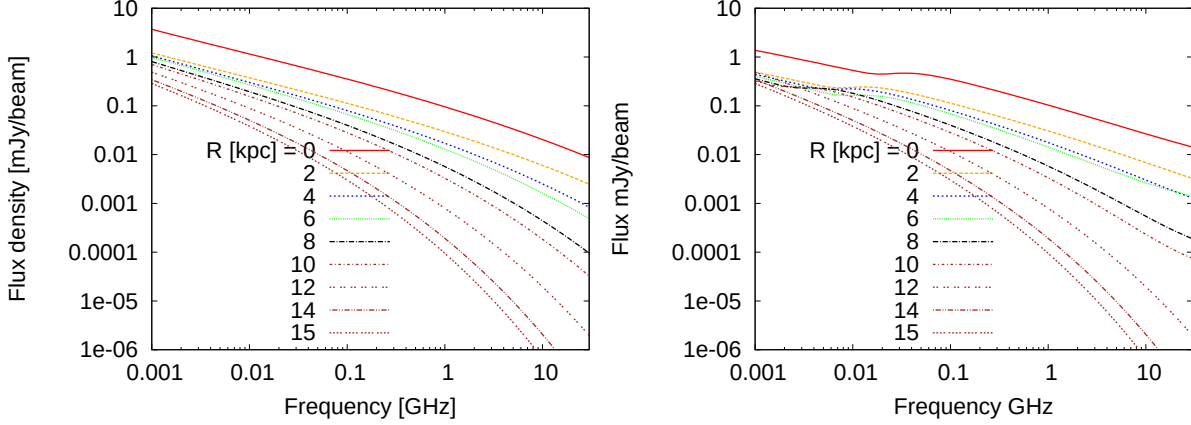


Figure 4.3: (Left) Local synchrotron spectra of a M51-like galaxy seen face-on at different distances along the galactic major axis from the centre. (Right) Local spectra of total flux densities at different distances along the galactic major axis from the centre.

depended parameters Da , Ea , C^a (Equation 4.2), and the parameters of thermal emission in Equation 4.1. Subsequently, we solved the radiative transfer equation (Equation 3.1) for various frequencies. At each frequency, we produced synthetic maps of radio emission (total, thermal, and synchrotron). Next, we integrated the flux densities at each frequency using these maps, and constructed a global spectrum. The steps were repeated for a number of models with different parameters. The obtained global spectra were compared with the observed spectrum of M51. We used the reduced chi-square χ_{red}^2 value to estimate the fit goodness. We also made a qualitative comparison of our results with the observed radial profile of radio emission of M51 and the radial spectral index profile from Mulcahy et al. (2014). Finally, we changed the parameters in steps by a small value ($\pm 10\%$) to find the model that gives the best fit. The resulting parameters are presented in Table 4.1.

Our best-fit model (Figure 4.2) reproduced well the observed radial profiles of radio emission and the spectral index of M51 (see Mulcahy et al. 2014). The modelled radial profiles of total radio emission show a break at $r \approx 2\text{kpc}$ corresponding to the transition between the inner and outer star-forming disks. Another break visible in the radial profile at $r \approx 10\text{kpc}$ matches the outer edge of the star-forming disk, and seems to be due to nearly absence of CRE sources at larger distances from the galactic centre. The global spectrum from modelling the galaxy shown in Figure 4.4 (left panel) fits well the literature data of M51, including flux density measurements from the LOFAR MSSS survey.

By changing the best-fit values from Table 4.1 by $\pm 20\%$, we were able to calculate to which extent the model parameters affect the fitted spectrum and the goodness of our fit. The calculated values of chi-square are summarized in Table 4.1. Figure 4.6 shows the calculated influence of the selected parameters on the model results. Changing by $\pm 20\%$ has no significant impact, and the ranges of the fitted model spectra are narrow, comparable to the data spread.

Finally, we used the model parameters that gave the best fit to observations of M51 to simulate galaxies with various inclination angles, solving again the radiative transfer equation for a number of frequencies, producing the maps and integrating the flux. The constructed global spectra for different inclination angles are shown in Figure 4.4 (right

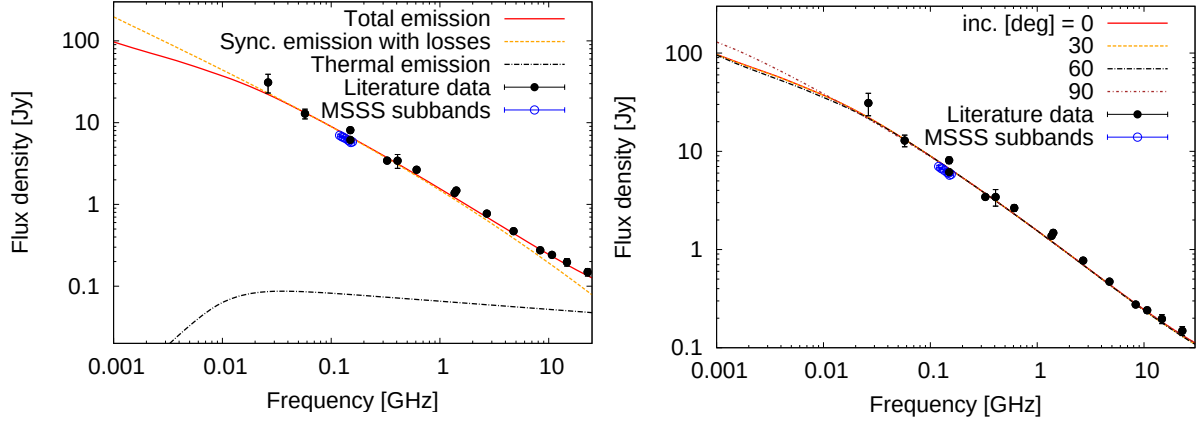


Figure 4.4: (Left) Resulting global spectrum of M 51-like galaxy from our 3D model as seen face-on (red solid line) with the synchrotron component without absorption (orange dotted line) and thermal free-free emission (black dashed line). Black solid circles denote literature data of M 51 used during the modelling and the interpolated flux density at 150 MHz from MSSS survey. For the sake of completeness, data from the individual MSSS sub-bands (blue circles) are also shown. (Right) Global spectra of M 51-like galaxy for different inclination angles of 0, 30, 60, and 90 degrees, respectively.

Table 4.1: Best-fit parameter values of the model to M 51 data and reduced chi-square values for the models where individual parameters were increased by 20% and decreased by 20%.

Parameter	Best fit	$\chi^2_{\nu}(+20\%)$	$\chi^2_{\nu}(-20\%)$
C_0^a	-4.1	1.58	1.58
C_1^a	-0.56	1.77	1.13
C_2^a	-0.05	1.13	1.63
C_3^a	-0.01	1.42	1.28
R_1^a	1.1 kpc	7.02	2.84
R_2^a	5.3 kpc	2.99	1.77
R_3^a	2.1 kpc	1.53	1.27
Z_1^a	0.3 kpc	3.57	2.03
Z_2^a	1.8 kpc	3.92	2.28
Da	-0.2	1.68	1.13
Ea	-0.05	1.50	1.24

panel). We also created synthetic maps of radio continuum emission, which are presented in Figure 4.7 for the selected frequencies and viewing angles.

4.3.2 Free-free absorption in typical nearby galaxies

Our model of the global spectrum of M 51-like galaxies shown in Figure 4.4 indicates only weak spectral flattening below 20 MHz and little influence of the galactic inclination. The low-frequency part of the global spectrum is only slightly flatter for low and moderately inclined galactic disks (0° - 30°) than for highly inclined galactic disks (90° , edge-on case). This is a consequence of the relatively small scale height of thermal electron distribution in M 51 (the thin disk: 0.1 kpc, the thick disk: 1 kpc, according to the formula 4.1) as compared to more extended synchrotron scale heights of the thin and thick disks, 0.3 kpc and 1.8 kpc, respectively (Table 4.1). Furthermore, due to the proportionality of thermal emission to N_e^2 , the scale height of thermal emission is half the size of the scale height of distribution of thermal electrons.

Our synthetic maps of radio emission (Figure 4.7) show strong free-free absorption

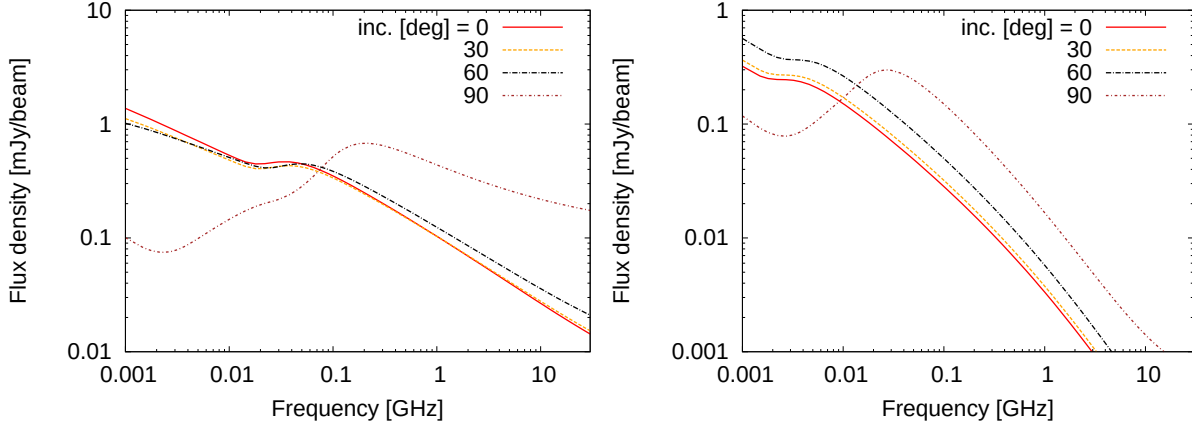


Figure 4.5: (Left) Local spectrum of the area around the galaxy centre for different inclination angles. (Right) Local spectrum of the region at 10 kpc from the center along the galactic major axis for different inclination angles.

Table 4.2: Optical depth τ along the line of sight in the modelled M51-like galaxy at different radial distances r from the galactic centre at two different frequencies.

r [kpc]	$EM(r)$ [cm^{-6}pc]	$\tau(150 \text{ MHz})$	$\tau(30 \text{ MHz})$
0	1800	0.032	0.93
1	700	0.012	0.36
10	14	0.0002	0.007

only at 30 MHz for highly inclined galaxies ($i \geq 60^\circ$). In order to perform quantitative analysis of free-free absorption, we calculated the optical depth at different radial distances from the centre of the modelled galaxy with inclination angle 0° (Table 4.2). The obtained optical depth $\tau = 0.032$ at 150 MHz in the galaxy center ($r = 0$ kpc) can reduce synchrotron emission by only $(1 - \exp(-0.032)) \times 100\% \approx 3\%$, while much stronger absorption is predicted by our model at 30 MHz, i.e. to 30% for the optical depth $\tau = 0.36$. However, such a high τ is actually expected only in the central region within radii of 1 kpc (Table 4.2).

Thus, we predict that in the observational range of frequencies there are no turnovers in the global spectra of M51-like galaxies caused by free-free absorption. This indicates that for typical late-type spiral galaxies with a moderate star formation, any curvature of global spectrum above 20 MHz results from curved local synchrotron spectra rather from free-free absorption. There is a number of mechanisms to possibly underlie such spectra in galaxies, like CREs energy losses and CREs propagation mechanism.

It is worth to remark that earlier observations of the Milky Way spectrum at very low frequencies revealed a turnover at about 3 MHz (Brown 1973, Ellis et al. 1982). The authors interpreted these findings as a result of free-free absorption by ionized gas in the Milky Way. Our model of the global spectrum of M51-like galaxies predicts no such turnover at low frequencies of few MHz. However, there is a vital distinction between observations of the Milky Way and of external galaxies. The spectrum of the Milky Way was necessarily measured from inside, while the spectra of external galaxies are obtained from outside. Due to our location within the plane of the Galaxy’s disk, it is likely that

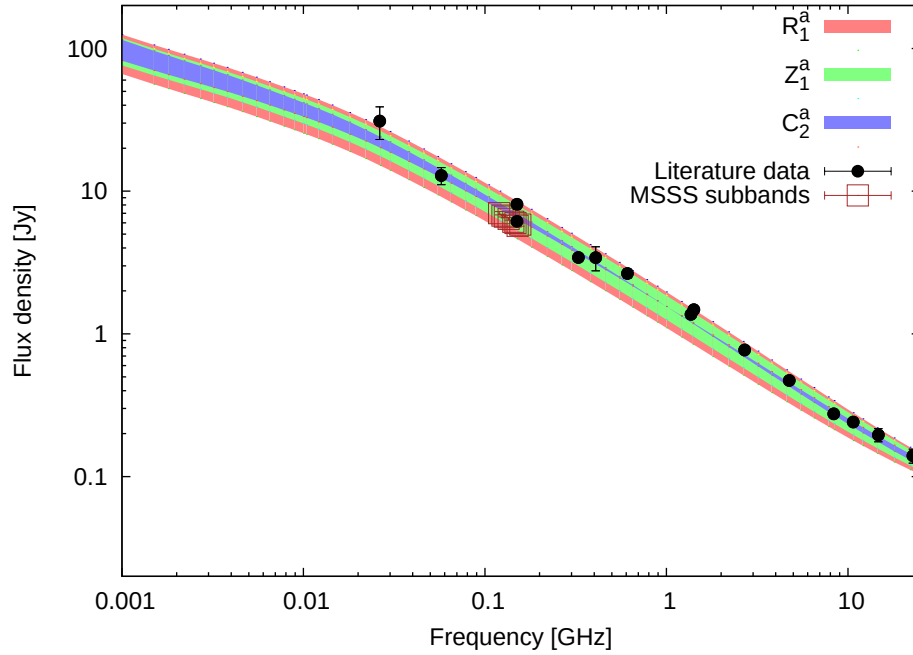


Figure 4.6: Ranges of the modelled global spectrum of M 51-like galaxy as affected by increasing and decreasing best-fit model parameters R_1^a , Z_1^a , and C_2^a by $\pm 20\%$. Black solid circles denote literature data of M 51 used during the modelling and the interpolated flux density at 150 MHz from the MSSS survey. For the sake of completeness, the data from individual MSSS sub-bands are also shown (brown rectangles).

we observe radio emission reduced by free-free absorption of ionized gas in the thin disk to produce a turnover at about 3 MHz. Therefore, assuming that the Milky Way is not essentially different from M 51, we anticipate from our modelling that there would be no turnover in the Galaxy’s global spectrum if seen from outside.

Our location inside the disk of the Milky Way could have another effect on measurements of integrated spectra of external galaxies. It is possible that the radio emission from other galaxies is observed through foreground Galactic thermal gas, which can absorb it, leading to a spectral turnover of their integrated spectra at about few MHz. Therefore, observing external galaxies over the celestial sphere at very low radio frequencies and analysing their low-frequency spectra could contribute significantly to our knowledge of the Galaxy’s ISM structure.

In our modelling, we also obtained local spectra of regions at different distances along the galactic major axis from the centre of a M 51-like galaxy seen under different viewing angles (Figure 4.5). The local spectra of the modelled galaxy centre are different from the modelled global spectra presented in Figure 4.4. The shape of local spectra of the central region highly depends on the tilt of the galactic disk. For almost edge-on cases (inclination angle $\approx 90^\circ$), due to strong free-free absorption in the thin disk, the local spectra from these regions show distinct turnovers at frequencies of about 100 - 200 MHz. Furthermore, the local spectra of the regions at 10 kpc radius depend also on the viewing angles, and for highly inclined galactic disks reveal turnovers at 20 - 50 MHz (Figure 4.5, right panel). Recent observations of NGC 891 (Mulcahy et al. 2018) revealed that the local spectra from star-forming regions in the disk are apparently strongly affected by

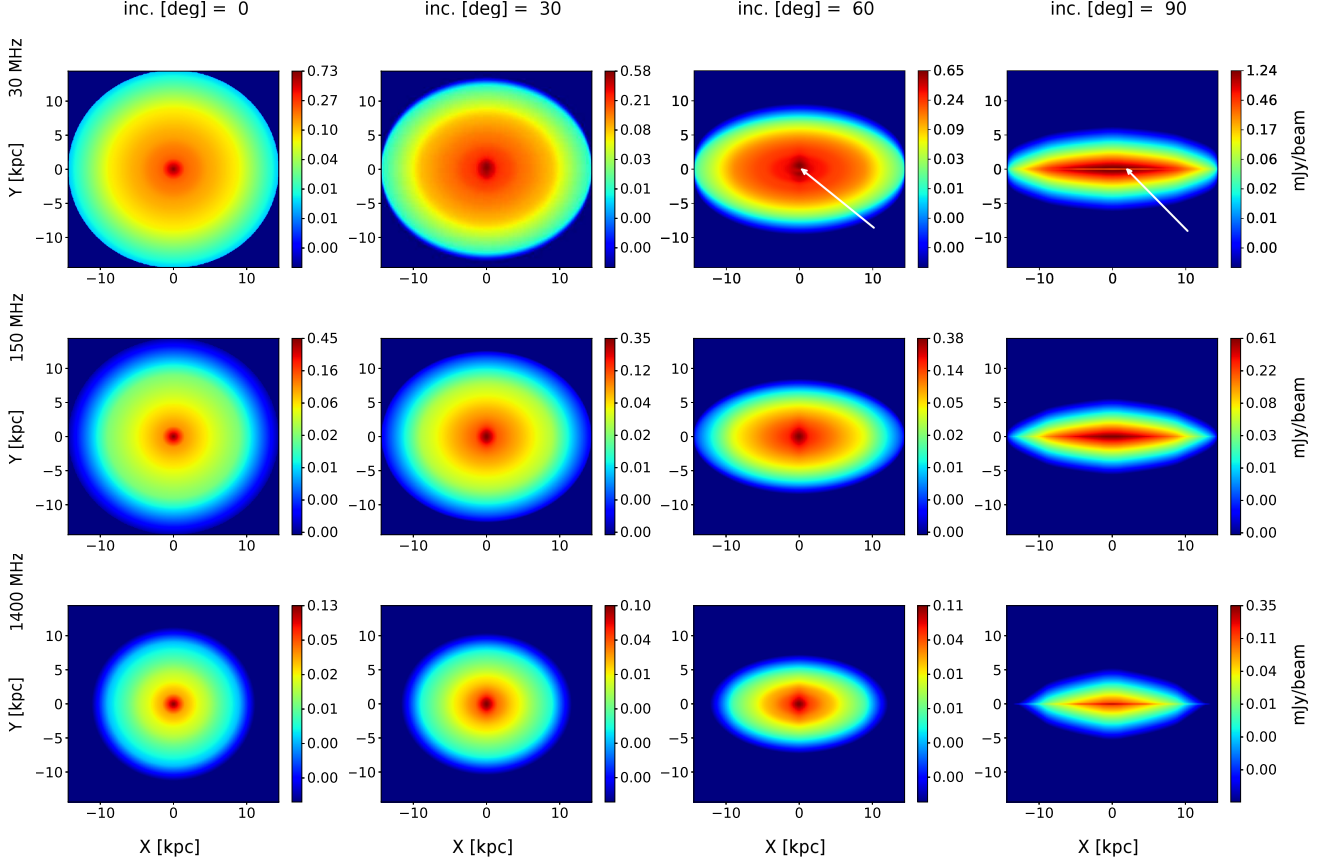


Figure 4.7: Synthetic radio emission maps of a nonstarburst M 51-like galaxy; rows from top to bottom show results at 30 MHz, 150 MHz, and 1400 MHz; columns from left to right show results for inclination angles of 0, 30, 60, and 90 degrees. The white arrows show regions with decrease of radio emission due to free-free absorption. The colour scale is in mJy/beam.

free-free absorption, which manifests itself as a values of the synchrotron spectral index between 150 and 1400 MHz that are greater than the spectral index of the injection spectra of CREs ($\alpha_{nt} \approx -0.6$).

We argue that for the less inclined galaxies ($i \leq 60^\circ$), the local spectra of their central parts show less distinct turnovers, typically at about 40 MHz, as well as a spectra rising towards lower frequencies (below 10 - 20 MHz) due to unabsorbed synchrotron emission in the thick disk. The local spectra of the regions at greater radii along the galactic major axis still show turnovers at lower frequencies down to 3 - 4 MHz ($r = 10$ kpc) (see Figure 4.3 and 4.5, right panels). At larger radii the local spectra resemble the synchrotron local spectra of total flux densities (see Figure 4.3, right panel), which can be ascribed to sudden disappearance of star-forming regions and thermal plasma.

4.4 Numerical modelling of M 82-like galaxies

4.4.1 Model parameters for M 82-like galaxies

We similarly modelled also M 82-like galaxies as a class of starburst galaxies visible at high viewing angles ($i \approx 80^\circ$). In this case, we assumed the cell size of 10 pc with the

total number of grid points of 2.7×10^8 . M 82 is a much more complex source than M 51, mostly due to its strong gravitational interaction with M 81, which triggered a high star formation rate within the starburst region of about $10 \text{ M}_\odot \text{ yr}^{-1}$ (Förster-Schreiber et al. 2003). The structure of the ISM is highly influenced by numerous massive star clusters and supernovae in the central starburst region, which drives an $\text{H}\alpha$ and X-ray-bright super wind (Westmoquette et al. 2009). A number of individual synchrotron sources in the circumnuclear starburst region are embedded in ionized gas with typical emission measures of about $10^5 \text{ cm}^{-6} \text{ pc}$ (Wills et al. 1997, Varenus et al. 2015). $\text{H}\alpha$ observations revealed presence of lower density ionised gas throughout the galactic halo reaching up to 1 kpc above the disk midplane (Shopbell & Bland-Hawthorn 1998). Thus in our model of M 82 we introduced a 3D distribution of ionized gas in the form of thin and thick exponential disks with $f_V = 1$. Both the scale lengths and heights of the disks were determined by fitting a double-exponential function to the vertical and horizontal profiles of $\text{H}\alpha$ emission derived from the $\text{H}\alpha$ map of M 82 from the Spitzer Infrared Nearby Galaxies Survey, (SINGS, Kennicutt et al. 2003). Accordingly, the 3D distribution of ionized gas is given by the following formula:

$$N_e(r, z) = A^b \exp\left(\frac{-r}{0.4 \text{ kpc}}\right) \exp\left(\frac{-|z|}{0.04 \text{ kpc}}\right) + B^b \exp\left(\frac{-r}{0.4 \text{ kpc}}\right) \exp\left(\frac{-|z|}{0.22 \text{ kpc}}\right) \quad (4.3)$$

where A^b and B^b are scale factors. The superscript b in this and the next equation denotes parameters that refer to modelling of M 82-like galaxies. The values of these scale factors were determined using the thermal fraction at 1.4 GHz estimated by Basu et al. (2012). In effect, in our modelling the integrated thermal emission constitutes 3% of integrated radio emission at 1.4 GHz.

We modelled unabsorbed synchrotron radio emissivity as an exponential thick and thin disks with the scale heights comparable to the scale lengths. The multi-frequency radio observations of M 82 showed that radio emission from the central region is dominated by very dense HII regions and supernova remnants, surrounded by a synchrotron halo extending up to the height of about $3'.5$ ($\approx 3.56 \text{ kpc}$) as seen at 0.33 and 1.4 GHz (Adebahr et al. 2013). Substantial asymmetry observed in the radio emission of the northern and southern galaxy disk, possibly caused by faster CREs energy losses or slower wind speeds in the southern outflow, is not included in our model. We either do not consider the emission from individual supernovae and star clusters. Hence, the synchrotron emissivity in our model is given by:

$$B_n(r, z) = C^b \left[\exp\left(\frac{-r}{R_1^b}\right) \exp\left(\frac{-|z|}{Z_1^b}\right) + F^b \exp\left(\frac{-r}{R_2^b}\right) \exp\left(\frac{-|z|}{Z_2^b}\right) \right] \quad (4.4)$$

where C^b and F^b are scale factors, R_1^b and R_2^b represent exponential scale lengths of the inner and outer synchrotron disks, and Z_1^b and Z_2^b are scale heights of the exponential thin and thick disks, respectively. The components in the above equation are similar to the constituents of M 82 considered in the modelling by Yoast-Hull et al. (2013), who, however, assumed a simplified cylindrical geometry. By analogy to the model of M 51-like galaxies, the scale factor C^b was introduced as a third-degree polynomial: $\log C^b(\nu) =$

Table 4.3: Best-fit parameter values of the model to M82 data and reduced chi-square values for the models where particular parameters were increased by 20% and decreased by 20%.

Parameter	Best fit	$\chi^2_{\nu}(+20\%)$	$\chi^2_{\nu}(-20\%)$
C_0^b	-4.2	2.46	2.18
C_1^b	-0.49	1.74	1.27
C_2^b	-0.02	0.23	0.25
C_3^b	-0.01	0.24	0.23
F_b	0.003	0.21	0.22
R_1^b	0.4 kpc	6.83	4.28
R_2^b	0.8 kpc	0.33	0.23
Z_1^b	0.13 kpc	2.26	1.34
Z_2^b	0.6 kpc	0.30	0.22
D^b	-0.2	0.27	0.23
E^b	-0.05	0.35	0.23

$$C_0^b + C_1^b \log \nu + C_2^b \log^2 \nu + C_3^b \log^3 \nu.$$

We applied a similar iterative fitting procedure as for M 51-like galaxies. The scale lengths R_1^b , R_2^b and scale height Z_1^b and Z_2^b were estimated by comparing the modelled and observed radio emission profiles along the major and minor axes using 0.33 and 1.4 GHz data (Adebahr et al. 2013). We assumed power-law functions: $R_1^b(\nu), R_2^b(\nu) \propto (\nu/\nu_1)^{D^b}$ and $Z_1^b, Z_2^b \propto (\nu/\nu_1)^{E^b}$, where ν_1 refers to 0.33 GHz, for the same reasons as while modelling of M 51-like galaxies. The values for the scale lengths R_1^b and R_2^b were approximated as 0.4 and 0.8 kpc, and for the scale heights Z_1 and Z_2 we obtained values of 0.13 and 0.6 kpc, respectively (see Table 4.3).

In the same way as in modelling of M 51-like galaxies, we used reduced chi-square to estimate the goodness of fit of integrated spectrum to the observed spectrum of M 82. The model that gave the best-fit spectrum is shown in Figure 4.8 (left panel) and the corresponding values of parameters are summarized in Table 4.3. As expected, the shape of the modelled global spectrum shows a flattening towards low frequencies. We present the values of the goodness of fit that correspond to changing the best-fit parameters by a factor of $\pm 20\%$. Apart from M 51-like galaxies, we calculated the ranges of the modelled global spectrum of M 82-like galaxies for decreased and increased best-fit parameters. The results for three selected parameters are shown in Figure 4.10. The obtained range of the modelled global spectra is narrow and comparable to data spread, also for the other parameters.

Using the parameters that gave the best-fit spectrum, we solved the radiative transfer equation for a number of viewing angles and frequencies. The results are shown in the form of synthetic maps of radio emission in Figure 4.11 for selected inclination angles and frequencies.

4.4.2 Free-free absorption in starburst galaxies

According to our modelling of starbursting objects like M 82, contrary to typical nearby galaxies like M 51, shows strong evidence of absorption effects in the integrated spectra

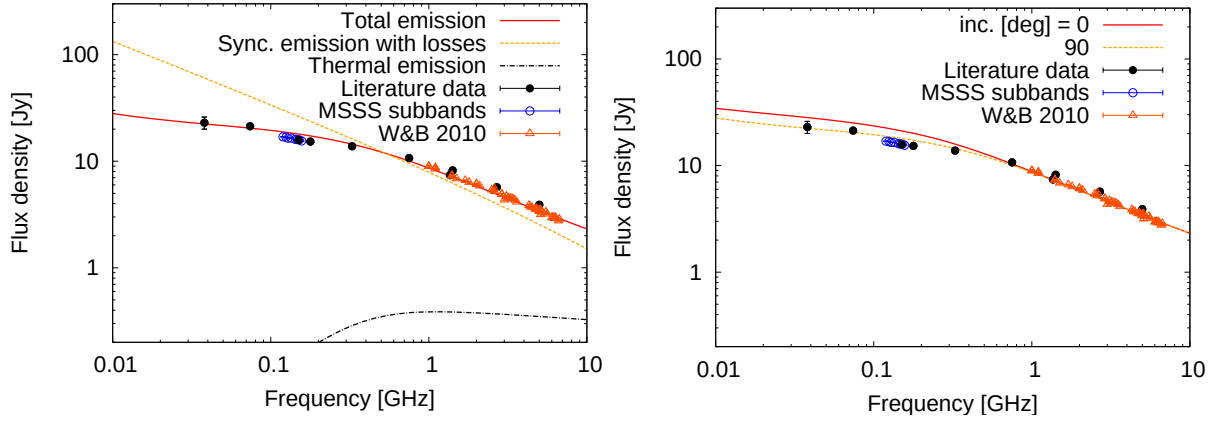


Figure 4.8: (Left) Global spectrum of a highly inclined M 82-like galaxy (red solid line) with the synchrotron component without absorption (orange dotted line) and thermal free-free emission with absorption (black dashed line). Black solid circles denote literature data of M 82 used during modelling, including the interpolated flux density at 150 MHz from the MSSS survey. For the sake of completeness, data from individual MSSS sub-bands (blue circles) and flux densities determined during the commissioning phase of the 42-element Allen Telescope Array (Williams & Bower 2010, orange triangles) are also shown. (Right) Comparison of global spectra of M 82-like galaxy for edge-on (orange dotted line) and face-on case (red solid line).

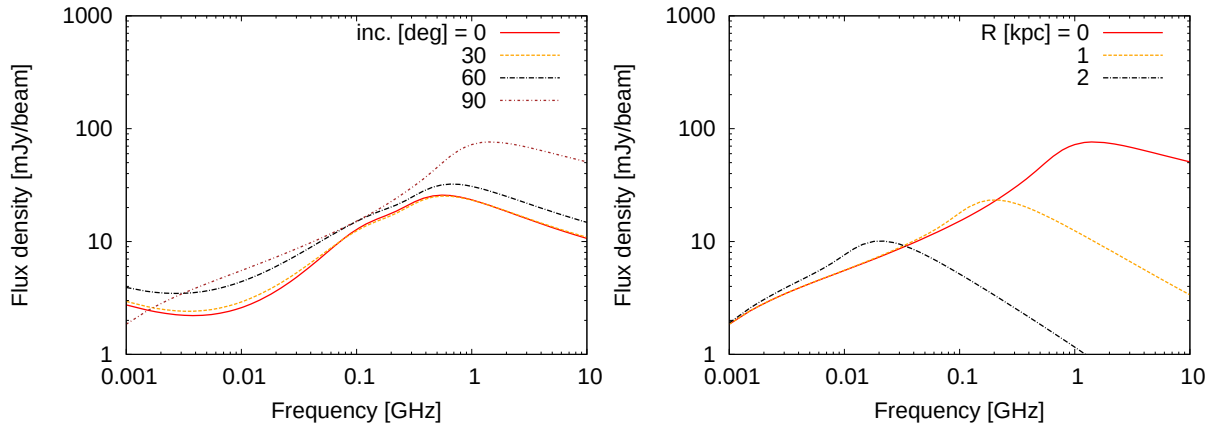


Figure 4.9: (Left) Local spectra from the galactic centre for different inclination angles. (Right) Local spectra at distances of 0, 1, 2 kpc from the galactic centre along the major axis for edge-on object.

for all inclination angles (Figure 4.8). The modelled integrated spectrum of M 82-like galaxies first slightly flattens and then slowly rises towards low frequencies. A gentle rise of the modelled spectrum at approximately 20 MHz is due to a contribution from the synchrotron halo, which becomes more extended than that to be seen at higher frequencies (see Figure 4.11). The spectral flattening observed between 200 - 400 MHz depends on the viewing angle and is more pronounced for highly inclined galaxy disks. In order to identify which region of the galactic disk has most influenced the shape of the modelled integrated spectrum, we analysed a vertical radio emission profile shown in Figure 4.12. Flattening of the global spectrum towards low frequencies can be attributed to emission from the inner part of the galaxy, at least to the height of about 500 pc. Our model predicts that the total radio emission seen beyond of 700 pc at frequencies above 30 MHz is not affected by free-free absorption.

The modelled local spectra of the central part of compact starbursts show a strong

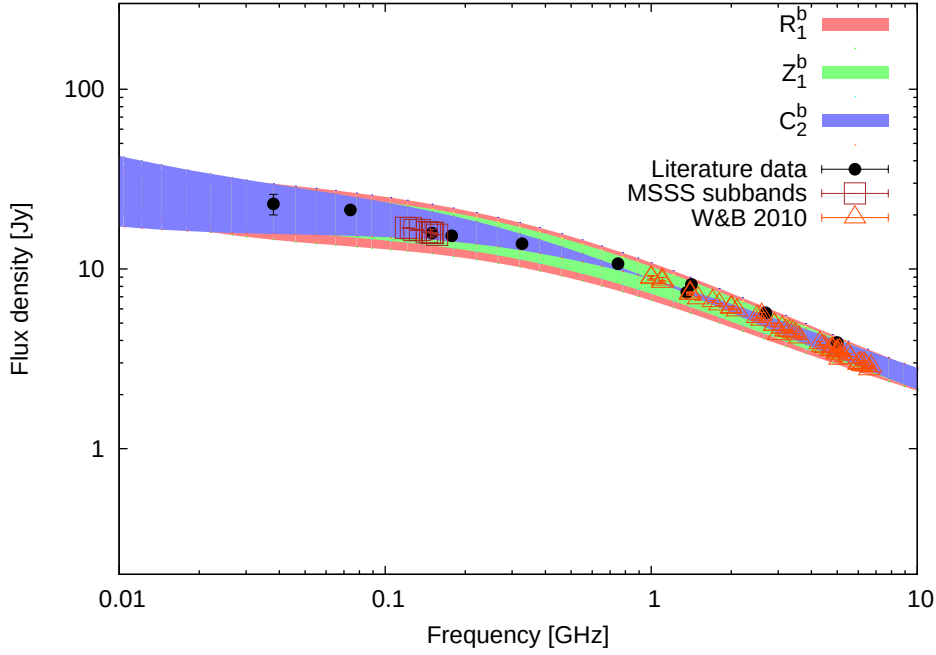


Figure 4.10: Ranges of the modelled global spectrum of M 82-like galaxy as affected by increasing and decreasing best-fit model parameters R_1^b , Z_1^b , and C_2^b by $\pm 20\%$. Black solid circles denote literature data of M 82 used during modelling including the interpolated flux density at 150 MHz from the MSSS survey. For the sake of completeness, data from the individual MSSS sub-bands (brown rectangles) and flux densities determined during commissioning phase of the 42-element Allen Telescope Array (Williams & Bower 2010, orange triangles) are also shown.

turnover at about 1 GHz for highly inclined galaxies, which moves to lower frequencies for smaller viewing angles, reaching about 500 MHz for face-on galaxies (Figure 4.9, left panel). Such strong absorption effects are caused by high emission measures in the modelled starburst region. The peak of the emission measure in the central part of the disk in our model is $2.3 \times 10^6 \text{ cm}^{-3} \text{ pc}$, and results from the assumed distribution of N_e (Eq. 4.3). In the case of M 51-like galaxies, the spectral turnover in the local spectra of the central parts of galaxy appears only for edge-on galaxies at about 200 MHz, because of lower values of emission measure than in the centre of M 82 (Figure 4.5, left panel).

In our modelling, we also obtained local spectra of regions at different distances from the centre along the galactic major axis of M 82-like galaxy seen as edge-on object (Figure 4.9, right panel). For greater distances from the central parts of galaxy, the local spectra strongly differ, showing turnovers at lower frequencies.

Unlike M 51-like galaxies, the effect of strong free-free absorption can be already seen in the maps of M 82 at 150 MHz as a significant drop of emission in the thin star-forming disk (Figure 4.11). This effect is caused by regions with mean modelled emission measure of several $10^5 \text{ cm}^{-3} \text{ pc}$, which well corresponds to the typical emission measures estimated by Wills et al. (1997) in the starburst core of M 82. The LOFAR HBA high-resolution observation of M 82 revealed a similar decrease of radio emission along the major axis of the galactic disk (Varenius et al. 2015). Our model predicts a relatively localized drop of radio emission at 150 MHz due to free-free absorption, while, at low frequency of 30 MHz (Figure 4.11, top-right panel) the decrease of radio emission can be seen as a much larger

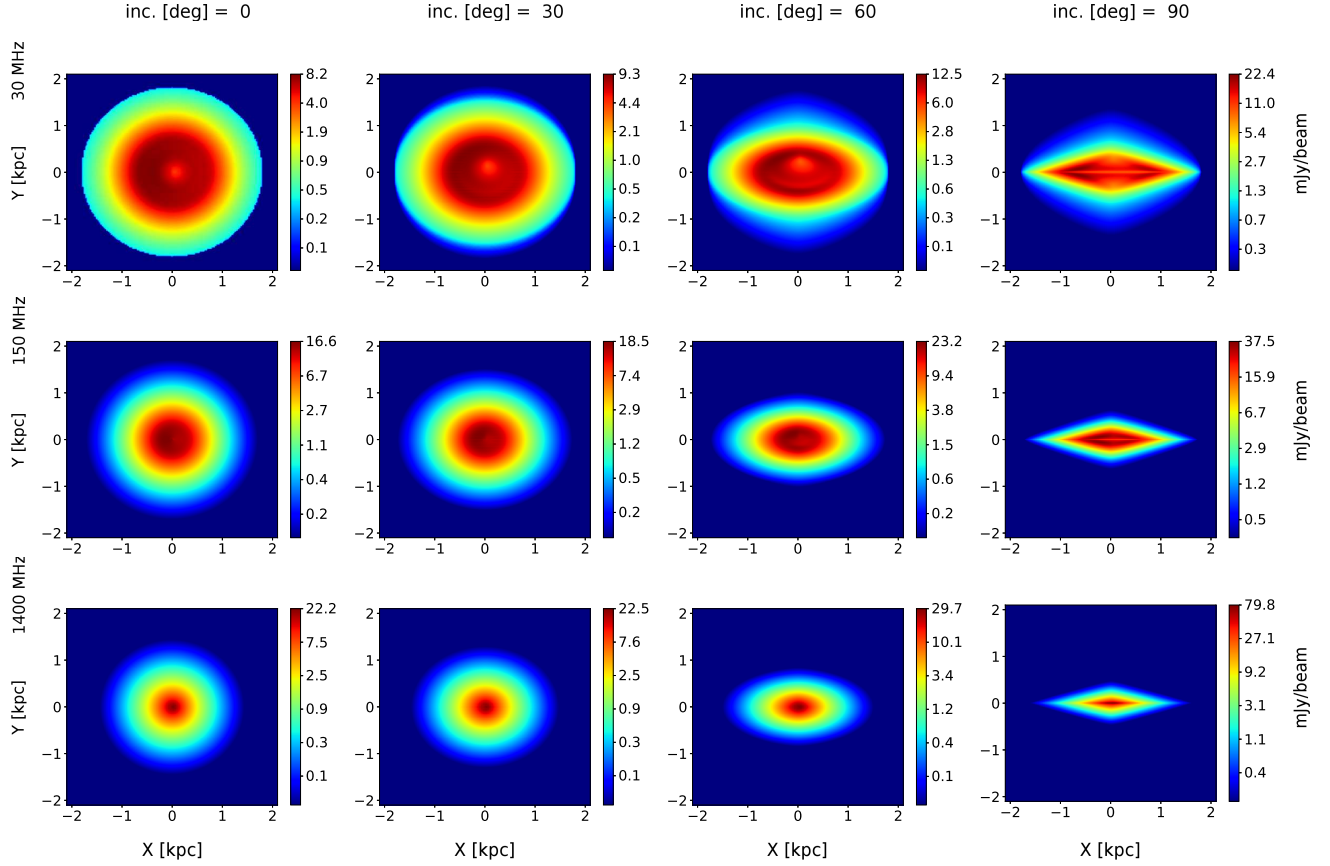


Figure 4.11: Synthetic radio emission maps of a starburst M82-like galaxy; rows from top to bottom show results at 30 MHz, 150 MHz, and 1400 MHz; columns from left to right show results for inclination angles of 0, 30, 60, and 90 degrees. The colour scale is in mJy/beam.

and wider depression all around the galactic centre. Therefore, we predict that future observations with the LOFAR LBA at about 50 MHz with international stations (angular resolution $\sim 1''$) could explore such wide drops of radio emission in the centre of galaxies.

With its high star-formation rate, M82 is yet not the most extreme case among observed starburst galaxies. Therefore, we can expect even stronger effects of free-free absorption in the integrated spectra of other violent star-forming objects and of more distant galaxies (high- z galaxies). Moreover, in the local spectra of these objects we should readily observe spectral turnovers due to free-free absorption at frequencies about 1 GHz or even higher. There arises a question why no such cases have been found with the sensitive instruments operating at higher frequencies over the last decade? The starburst galaxies are actually rare in the local Universe, and so the population of galaxies with clearly identified spectral curvature due to free-free absorption is rather small. Interestingly, the studies of evolution of spectral curvature in star-forming galaxies out to high redshift by Calistro Rivera et al. (2017) have revealed no traces of evolution within the galactic sample. Further evidence of free-free absorption in the integrated spectra of starburst galaxies (spectral turnovers between 90 to 500 MHz) was recently reported by Galvin et al (2018). However, their results refer to a sample of galaxies at moderate redshifts ($0.067 < z < 0.227$).

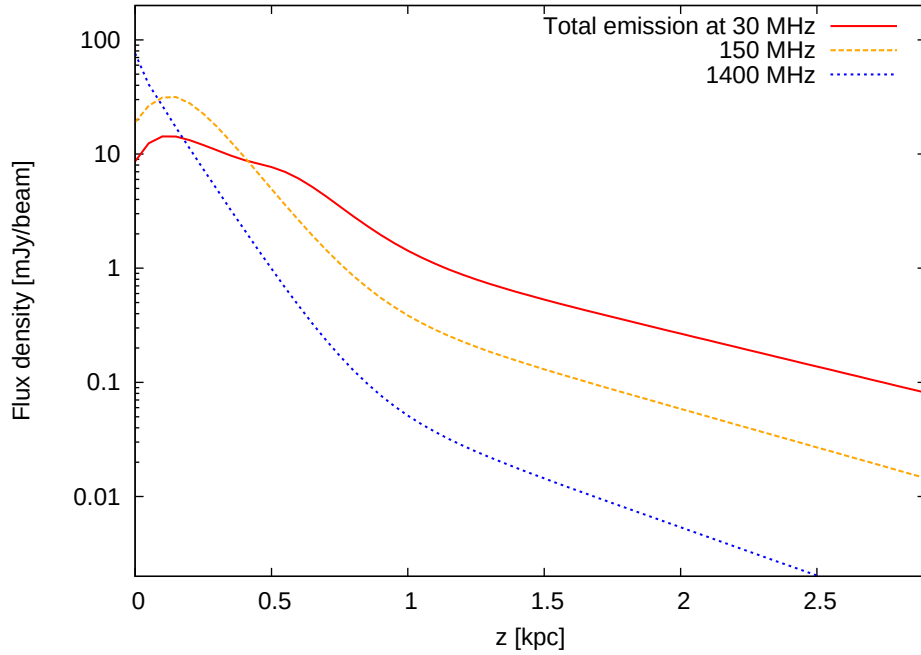


Figure 4.12: Modelled vertical profiles of the total radio emission of M82-like galaxy seen edge-on at 30, 150, and 1400 MHz.

4.5 Flattening of synchrotron spectrum

In our modelling, we introduced curvature of local synchrotron spectra for both M51- and M82-like galaxies. Such curved spectra can result of CREs energy loss mechanisms, for example, synchrotron or IC losses, which can lead to steepening of spectrum at higher frequencies. The steep spectra of high-energy CREs are more commonly to be seen in the galactic outskirts due to CREs transported off the star-forming disk (Mulcahy et al. 2014). Furthermore, ionization losses, which are more effective at low frequencies, can cause flattening of low-frequency part of synchrotron spectrum. In effect, the observed synchrotron spectrum could be flatter at low frequencies and steeper at high frequencies than the power-law spectrum with a constant spectral index (Murphy 2009).

In order to estimate relative contributions from different energy loss mechanisms of CREs, we calculated particular cooling timescales of CREs (synchrotron, IC, ionization and bremsstrahlung) as a function of frequency. The exact formulas that we used are presented in Appendix A. In our derivation we assumed the strength of magnetic fields of $10 \mu\text{G}$ and the atomic hydrogen densities of 1 cm^{-3} , which are typical values for M51 and the other nearby star-forming galaxies.

It can be seen (Figure 4.13, left panel) that for typical nearby galaxies timescales of ionization and bremsstrahlung cooling become shorter than the timescale of synchrotron cooling below about 0.2 and 1 GHz, respectively. Our calculations show that for the nearby star-forming galaxies, local synchrotron spectra down to 0.15 GHz are mostly dominated by synchrotron losses, which are able to produce spectral steepening or break at higher frequencies. Therefore, for the purpose of our modelling, we assumed the local synchrotron spectra with curvature due to synchrotron losses (Figure 4.3, left panel). In

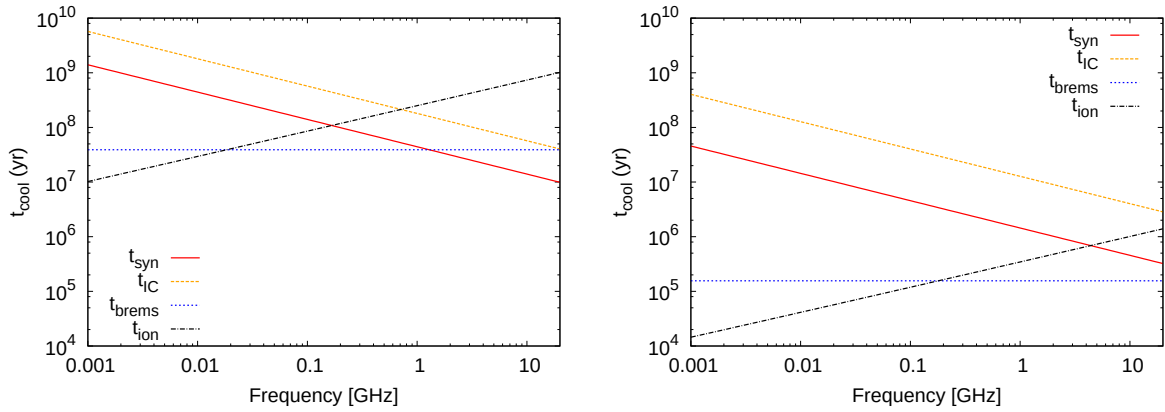


Figure 4.13: (Left) The synchrotron, IC, bremsstrahlung and ionization loss cooling timescales as a function of frequency calculated for a typical nearby galaxy like M 51 assuming strengths of magnetic field strength of $10 \mu\text{G}$, atomic hydrogen densities of 1 cm^{-3} , and $U_{\text{rad}} = 10^{-12} \text{ erg cm}^{-3}$. (Right) The cooling timescales for synchrotron, IC, bremsstrahlung and ionization losses for a compact starburst region assuming magnetic field strength of $98 \mu\text{G}$, lower limit of atomic hydrogen density of 250 cm^{-3} , and $U_{\text{rad}} = 4.43 \times 10^{-11} \text{ erg cm}^{-3}$.

order to calculate a cooling timescale for starburst galaxies, we used the lower limit of density of neutral gas of 250 cm^{-3} , the magnetic field strength of $98 \mu\text{G}$, and the energy density $U_{\text{rad}} = 4.43 \times 10^{-11} \text{ erg cm}^{-3}$ in the core of M 82, following Adebahr et al. (2013). For the starburst core of M 82 we obtained shorter timescales of ionization cooling than the timescale of synchrotron cooling below about 4 GHz, where the bremsstrahlung is dominant (Figure 4.13, right panel). Moreover, the ionization loss becomes the principal energy loss mechanism for CREs below 100 MHz, which can lead to flattening of synchrotron spectrum. The joint effect of free-free absorption and ionization losses on the shape of integrated spectrum of galaxies is yet not determined. However, our model of M 82-like galaxies involving only absorption by ionized gas reproduced well the integrated spectrum of M 82.

Recently, Klein et al. (2018) showed that the model of spectrum with a break or exponential decline at the frequencies beyond 1 GHz can reproduce well the integrated spectra of most spiral and dwarf galaxies. Apart from CREs energy loss mechanisms, such a break or steepening of high-frequency spectrum can be caused by advective transport in a galactic wind or a recent cutoff in the injected CREs. However, Niklas & Beck (1997) and Tabatabaei et al. (2017) using models with no breaks in the synchrotron spectrum, were still able to fit well spectra of most galaxies from their sample.

Our modelling in Chapter 3 revealed that the studies basing on the integrated spectra only, which necessarily require assuming constant break frequency and thermal fraction in the entire galaxy disk, are of very limited usability. Unlike all the previous studies basing solely on the integrated spectra of galaxies, in our modelling of M 51-like objects the local synchrotron spectra differ significantly across the galaxy disk (Figure 4.3, left panel). The shape of local spectra and spectral breaks/flattening, are strongly correlated with the energy losses of CREs, their propagation mechanism and distribution of the ISM. However, different spectral features of local spectra are smeared out after adding the emission in constructing the integrated spectrum (see Lisenfeld & Völk 2000, Basu et al. 2015). Accordingly, the proper interpretation of the integrated radio spectra of galaxies requires

spatially resolved radio observations and modelling of spatial structure and composition of the ISM as well as CRE propagation. The upcoming release of data from the LOFAR Two-metre Sky Survey (LoTSS, Shimwell et al. 2017) will provide the still lacking so far high-resolution observational data for a number of galaxies at low frequencies.

4.6 Conclusions

In order to interpret and discuss processes that shape the low-frequency radio spectra of galaxies, I performed numerical modelling of radio emission. First, I investigated how clumpy medium influence the low-frequency spectra of galaxies. I show that the thermal medium filling factor f_V does not change the frequency of spectral turnover due to thermal absorption (see Figure 4.1, left panel). However, the clumpy nature of absorbing medium reduce the depth of low frequency depression in galaxy spectra which can be used as a tool to constrain the value of f_V .

Subsequently, I thoroughly modelled M 51-like galaxies, which represent low-SFR objects seen at low inclination, and M 82-like galaxies, which represent starburst galaxies visible at high inclination. I used for the first time the low-frequency LOFAR data from the MSSS survey as well as other available literature data to construct observational spectra of M 51 and M 82 galaxies. My modelling of galaxies with low-SFR basing on observations of M 51 led to the following conclusions:

- Free-free absorption can influence the global spectrum of M 51-like galaxies at frequencies only below 20 MHz (Figure 4.4). Accordingly, I suggest that a weak flattening observed in the integrated spectra of some galaxies above this frequency can result from the curvature in the synchrotron spectrum due to energy losses and diffusion of CREs.
- Local radio spectra of central parts of galaxies, obtained from our modelling of M 51-like galaxies differ much from their global spectra, and can even reveal spectral turnovers caused by free-free absorption in the edge-on objects. There could be spectral turnovers at frequencies of about 100 - 200 MHz (Figure 4.5, left panel), but without high-resolution radio observations it is not possible to reveal them.
- My models indicate that even galaxies with simple, power-law-like, global spectra can locally show significantly curved spectra, especially far away from the galactic centres. Therefore, the integrated spectra cannot be properly interpreted without considering supplementary data on the properties of the local ISM within the galaxies.

My modelling of galaxies with high-SFR based on observations of M 82 yielded the following results:

- The modelled M 82-like galaxies show much stronger free-free absorption effects in their global radio spectra than M 51-like galaxies, independently of viewing angle (Figure 4.8). Going towards low frequencies, the global spectra first flatten between

200 - 400 MHz, depending on the viewing angle, and then gently increase at about 20 MHz, due to growing contribution of the galactic synchrotron halo. This could explain why the simple models involving just well-mixed thermal- and synchrotron-emitting gas occupying the same region cannot reproduce the observed integrated spectrum of M 82.

- My synthetic maps of radio emission of M 82-like galaxies at 150 MHz, as compared to M 51 maps, show strong absorption mainly along the thin disk, whereas at lower frequencies at about 30 MHz, my model predicts a much more substantial decrease of radio emission further around the galaxy centre (Figure 4.11).
- In my modelling of M 82-like galaxies, local spectra of the central starbursts reveal strong turnovers at frequencies about 1000 MHz for the galaxies viewed edge-on and about 500 MHz for the weakly inclined galaxies (Figure 4.9, left panel). Therefore, I predict much stronger free-free absorption effects in the radio spectra of (U)LIRGs and more distant galaxies with exceptionally high-SFR.

Despite the fact that our 3D modelling enabled me to reproduce flattening of the integrated spectrum of M 82 while assuming only free-free absorption, the low-frequency spectra can be affected by ionization losses as well, especially in starburst regions. However, the influence of ionization losses on the low-frequency radio emission of galaxies is still poorly understood.

I also predict a possible influence of the Milky Way foreground gas on the external galactic spectra at frequencies below 10 MHz. To confirm this effect, observations of external galaxies at very low radio frequencies throughout the celestial sphere are needed. These low-frequency observations would require radio interferometers located outside our planet, in space or ideally on the surface of the Moon to eliminate human-produced RFI and the influence of the Earth's ionosphere. The forthcoming more sensitive and high-resolution LoTSS HBA (Shimwell et al. 2017) survey and particularly the planned LOFAR LBA survey at about 50 MHz, as well as new observations of galaxies with the Murchison Widefield Array (WMA, Hurley-Walker et al. 2017) will be very helpful. Furthermore, broad-band polarization observations covering both low and high frequencies could provide the key data to explore thermal galactic component responsible for free-free absorption.

My modelling underlines also the need to observe compact regions in galaxies at very low frequencies and at very high angular resolution, which are required to constrain models of the components and properties of the ISM. Future high-resolution observations of LOFAR with Polish and other international stations can provide suitable observational data.

CHAPTER 5

Summary

The work carried out in this thesis was aimed at studying the low-frequency radio emission and radio spectra of galaxies. During the course of this thesis, I performed data reduction of the LOFAR HBA observation of a grand-design spiral galaxy NGC 6946, followed by a detailed analysis of its integrated spectrum and low-frequency radio continuum emission. In order to interpret the integrated spectra of galaxies at low frequencies, I developed software to perform 3D numerical modelling of radio emission from galaxies. Using this method, the influence of various physical parameters of galaxies as well as of projection effects on the shape of integrated spectra of galaxies were investigated. To explore the difference between the processes that shape spectra of the typical nearby galaxies and starburst galaxies, I modelled thoroughly M 51-like and M 82-like galaxies, as low- and high-SFR cases, respectively. I found that M 51 was studied in more detail than NGC 6946 in the past, in particular as regards ionized gas, hence this object was modelled as a case study of nearby galaxies. Modelling of high-SFR galaxies was based on the intensively studied M 82, which was also observed with the 42-element Allen Telescope Array in an unprecedented broadband integrated spectrum from 1.0 to 7.0 GHz with a spacing of 0.1 GHz. I used for the first time the low-frequency LOFAR data from the MSSS LOFAR survey as well as other available literature data to construct the observational low-frequency spectra of M 51 and M 82 galaxies.

My observations of NGC 6946 with the LOFAR HBA at 144 MHz, enabled me to detect a diffuse synchrotron envelope, more extended than the optical and high-frequency radio emissions, reaching a distance of up to 18 kpc from the galactic centre. This galaxy looks therefore “fatter” at low frequencies and is currently the second case showing such effect seen in face-on galaxies besides M 51. This fattening effect is quantitatively best described by the scale lengths of radio emission, which are about twice larger at 144 MHz than at 1400 MHz. Such results can be explained by propagation of CREs which in case of NGC 6946 is well described by diffusion process. According to this concept, the observed synchrotron emission at the outskirts of the galaxy at 144 MHz results from the low-energy population of CREs, propagating to larger distances from the site of their origin due to lower energy losses than at higher frequencies. I report also that the radial profile of synchrotron emission at 144 MHz reveals two breaks. The first break at distance of about 3 kpc from the galactic centre corresponds with the transition between thin and thick galactic disks, while the second one between the inner and outer disks at about

9 kpc, seen as decline of exponential scale length at 144 MHz from 6.71 to 3.65 kpc, can be ascribed to rapid decrease of star-forming regions and sources of CREs.

I have shown that the integrated spectrum of NGC 6946 does not reveal any flattening due to free-free absorption or ionization losses. This finding is in accordance with the previous LOFAR HBA observations of another nearby galaxy, M 51, which also shows a simple power-law spectrum towards low frequencies. However, the local spectrum from the central parts of NGC 6946 reveals a spectral turnover below 300 MHz, indicating the presence of free-free absorption, presumably caused by ionized gas within the HII complexes.

For a better understanding of the low-frequency spectra, I developed a 3D numerical model of radio emission of star-forming galaxies, solving the radiative transfer equation and taking into account the projection effects. I show that the simple modelling of galaxy spectra in the form of well-mixed thermal and synchrotron media (Condon 1992) is not sufficient to reproduce actual spectra of galaxies, even those of the starburst type. It is necessary to introduce frequently observed galactic halos, their size, intensity, and synchrotron spectral index, strongly influence the model spectra. I also investigated how clumpy ionized medium influences the modelled low-frequency spectra of galaxies. I showed that the thermal gas filling factor does not change the frequency of spectral turnover due to free-free absorption. However, the filamentary absorbing medium reduces the depth of low-frequency depression in galaxy spectra caused by absorption.

In the course of this thesis, I have solved an apparent paradox that the curved spectra seen in the M51SS galaxies at low frequencies cannot be caused by free-free absorption, while the strong free-free absorption effects seem to be the only reasonable explanation for the low-frequency radio emission in e.g. the central parts of M 82, and NGC 253 as well as in some regions in the centre of the Milky Way (Chyży, Jurusik et al. 2018). According to my 3D modelling of galactic radio emission, these observational results can be reconciled by assuming curved synchrotron spectra of galaxies due to energy losses and diffusion of CREs. The above conclusion appeared clear when showing that the modelled free-free absorption can affect the shape of integrated spectra of M51-like galaxies at frequencies only below 20 MHz.

Moreover, I found that M 51-like galaxies with simple power-law-like integrated spectra, can locally reveal significantly curved spectra, especially at the galactic outskirts. Furthermore, the local spectra from the central parts of the M 51-like galaxies show turnovers around 100 - 200 MHz in the edge-on ones, and less distinct turnovers below 100 MHz as well as a spectral rising towards low frequencies for the low-inclined objects. The performed modelling leads me to the next conclusion that interpretation of integrated spectra of galaxies cannot be carried out properly without additional data on the properties of the local ISM within the galaxies.

My modelling of galaxies with high-SFR, like M 82, reveals much stronger free-free absorption effects in their integrated spectra than for M 51-like galaxies. According to my modelling the integrated spectra of M 82-like galaxies first flatten towards low frequencies between 200 - 400 MHz, depending on the inclination angle, and subsequently show gently raise of radio emission at about 20 MHz, caused by increasing contribution of the galactic synchrotron halo. Similar spectral features were observed at higher frequencies, below

the spectral turnovers at about 1000 MHz, in the integrated spectra of ultra-luminous infrared galaxies.

Local radio emission from central parts of starburst galaxies is heavily influenced by free-free absorption. The modelled local spectra of M82-like galaxies show a distinct turnover at about 1000 MHz for highly inclined galaxies and about 500 MHz for weakly inclined galaxies. My synthetic maps of radio emission of M82-like galaxies reveal depression of intensities along the thin disk at 150 MHz, while much more absorption around the galactic centre is predicted towards lower frequencies.

Throughout this thesis, I emphasize the importance of further low-frequency observations. In order to confirm our modelling predictions, observations of galaxies at frequencies around and below 50 MHz, are desirable. I have submitted a proposal for observations of NGC 6946 with the LOFAR LBA at frequencies down to 30 MHz, which could enable me detection of radio emission even more extended than that at 144 MHz. According to the modelling presented in this thesis, one can expect free-free absorption to become prominent at such low frequencies. I also calculated that ionization losses of CREs can probably affect low-frequency spectra, particularly in dense regions of the star-forming galaxies. However, the joint effect of those energy losses is still poorly understood. New sensitive and high-resolution observational data will soon become available e.g. from low-frequency surveys as LoTSS HBA (Shimwell et al. 2017), and especially LOFAR LBA survey at about 50 MHz, allowing further studies of radiation processes in galaxies.

The model of M51-like galaxies presented in this work predicts a possible influence of the Milky Way foreground ionized gas on the spectra of external galaxies at frequencies below 10 MHz. Such an effect could be confirmed only by radio observations from outside the Earth, in the space or ideally from the surface of the Moon.

Appendices

APPENDIX A

Cosmic-ray electron energy losses

CREs diffuse from their origin sites through the ISM, and their motion is a result of random scattering by irregularities in the magnetic field. The diffusing CREs experience energy losses and gains at different points on their paths. The evolution of the energy spectrum of CREs travelling from their sources, on assumption of continuous energy losses and supply of new particles, is described by the diffusion-loss equation (Longair 2011):

$$\frac{dN(E)}{dt} = D\nabla^2 N(E) + \frac{\partial}{\partial E} [b(E) N(E)] + Q(E) \quad (\text{A.1})$$

where, D is the diffusion coefficient, which describes motion of CREs. The $N(E)$ is the CREs number density. The rate at which CREs are injected is given by $Q(E)$. The energy losses and gains of the charged particles are included in the following term:

$$-\frac{dE}{dt} = b(E) \quad (\text{A.2})$$

where, if $b(E) > 0$, then the particles lose their energy.

While propagation away from their injection sites, CREs can lose their energy due to interactions with other particles, matter, magnetic field and radiation. Below the particular loss mechanisms are described in the form of time derivatives of the particle energy:

- **Ionization losses** occur when charged particles interact with neutral particles of medium, and electrons are torn off atoms of medium. As a result of ionization losses, atoms after encounters remain in an ionized state. The energy loss for neutral hydrogen interacting with electrons is given by (Longair 2011):

$$-\left(\frac{dE}{dt}\right)_{ion} = 7.64 \times 10^{-15} \left(\frac{n_{HI}}{\text{m}^{-3}}\right) (3\ln\gamma + 19.8) \text{ eV s}^{-1} \quad (\text{A.3})$$

where $\gamma = (1 - v^2/c^2)^{-1/2} = E/m_e c^2$ is the Lorentz factor, and n_{HI} is the number density of hydrogen atoms per m^3 .

- **Bremsstrahlung losses** are caused by free-free interactions of charged particles, accompanied by the emission of bremsstrahlung radiation (free-free emission). The accelerated particle emits a photon, losing its kinetic energy. For the ultra-relativistic

electrons, non-thermal bremsstrahlung can be estimated using the following formula:

$$-\left(\frac{dE}{dt}\right)_{brem s} = 4nZ^2r_e^2\tilde{\alpha}c\tilde{g}E \quad (\text{A.4})$$

where, Z is the atomic number, r_e is the classical electron radius, $\tilde{\alpha}$ is the fine-structure constant, c is the speed of the light, and the Gaunt factor $\tilde{g}$, which can have different forms for various kind of medium. The energy of CRE is denoted by E .

The Gaunt factor for neutral hydrogen can be approximated by $\tilde{g} = (183Z^{-\frac{1}{3}}) - 1/8$, and the non-thermal bremsstrahlung losses for electrons in neutral hydrogen are:

$$-\left(\frac{dE}{dt}\right)_{brem s} = 3.66 \times 10^{-22} \left(\frac{n_{HI}}{\text{m}^{-3}}\right) \left(\frac{E}{\text{eV}}\right) \quad (\text{A.5})$$

where n_{HI} is the number density of HI per m^3 .

- **Synchrotron losses** arises due to the synchrotron radiation of CREs, and are described by (Longair 2011):

$$-\left(\frac{dE}{dt}\right)_{syn} = \frac{4}{3}\sigma_T c\gamma^2 U_{mag} \quad (\text{A.6})$$

where, σ_T is the Thompson scattering cross-section, and U_{mag} is the energy density of the magnetic field, which is $\propto B^2$.

- **Inverse Compton losses** are due to inverse-Compton radiation, in which the energy of electrons travelling through a radiation field is partly transferred to photons. The inverse-Compton losses of ultra-relativistic electrons scattered in the radiation field with the energy density U_{rad} are:

$$-\left(\frac{dE}{dt}\right)_{IC} = \frac{4}{3}\sigma_T c\gamma^2 U_{rad} \quad (\text{A.7})$$

- **Adiabatic losses** occur if a gas of relativistic electrons expands and its inertial energy E is reduced depending on the velocity gradient $\vec{\nabla} \cdot \vec{v}$ of expanding medium. The following expression describes electron energy-loss rate due to adiabatic losses:

$$-\left(\frac{dE}{dt}\right)_{adiab} = \frac{1}{3}(\vec{\nabla} \cdot \vec{v}) E \quad (\text{A.8})$$

Energy losses of CREs are also usually investigated using their time scales t , defined as:

$$t = \frac{E}{dE/dt} \quad (\text{A.9})$$

The time scales of the above energy-loss mechanisms are provided in Table A.1 (after Murphy 2009) and used in Section 2.7.2.

Table A.1: Time scales of different CREs energy losses.

Time scales	
t_{ion}	$4.1 \times 10^9 (\frac{E}{\text{GeV}}) (\frac{n}{\text{cm}^{-3}})^{-1} [3 \ln(\frac{E}{\text{GeV}}) + 42.5]^{-1}$
t_{brems}	$3.96 \times 10^7 (\frac{n}{\text{cm}^{-3}})$
t_{syn}	$1.4 \times 10^9 (\frac{\nu}{\text{GHz}})^{-1/2} (\frac{B}{\mu\text{G}})^{-3/2}$
t_{IC}	$5.7 \times 10^7 (\frac{\nu}{\text{GHz}})^{-1/2} (\frac{B}{\mu\text{G}})^{1/2} (\frac{U_{rad}}{10^{-12} \text{erg cm}^{-3}})$
t_{adiab}	$1.0 \times (\frac{h}{\text{kpc}}) (\frac{V}{\text{km s}^{-1}})$

where, E is the energy of CREs at frequency ν , n is the density of neutral gas, B denotes the magnetic field strength. The total energy density of the radiation field is represented by U_{rad} . The disk scale height is denoted by h , and V is the speed of galactic wind.

APPENDIX B

Interstellar medium

The stars in galaxies are immersed in an extremely tenuous medium of cosmic-rays, gas, dust, and magnetic fields. These components can be directly observed but there is also dark matter, accounting for 90% of the total mass of the galaxy, which can be detected only through its gravitational effects. The hadronic content of galaxies, apart from the stars, in the form of gas ($\sim 99\%$) and dust ($\sim 1\%$), is composed of hydrogen ($\sim 91\%$), helium ($\sim 9\%$), and trace amounts of heavier elements (0.01%). This so-called interstellar medium (ISM), plays an important role in the life cycles of stars as well as in galactic evolution. The ISM divides into the following main phases: molecular clouds, cold neutral medium (CNM), warm neutral medium (WNM), warm ionized medium (WIM), and hot ionized medium (HIM). Their typical physical parameters are provided in Table B.1 (after Haverkorn & Spangler 2014). The molecular clouds and HII regions are often considered as belonging to CNM and WIM, respectively. The supernova explosions, shocks, and turbulences in the ISM produce a number of spectacular structures as clouds, filaments, and voids. The ionization and cooling processes within the gas both depend on particular structures of the ISM, thus the filling factor of each phase is of much importance (see Table B.1).

Table B.1: Typical physical parameters of interstellar medium.

Phase	Density (cm^{-3})	Temperature (K)	Filling factor (%)
Molecular clouds	$200 - \geq 10^5$	≤ 100	0.05
Cold Neutral Medium (CNM)	$10 - 100$	~ 100	1
Classical HII regions	$5 - 10$	8000	3.0×10^{-3}
Warm Neutral Medium (WNM)	$0.1 - 0.5$	6000 – 8000	30
Warm Ionized Medium (WIM)	$0.1 - 0.5$	≥ 8000	25
Hot Ionized Medium (HIM)	5×10^{-3}	10^6	50

The WIM consists of dense HII regions in the disk, surrounded by diffuse ionized gas (DIG) in the form of layers extending to high galactic latitudes. Observations of the Milky Way and external galaxies revealed that the ionized phases of the ISM, the warm and hot ionized gas, occupy most of the interstellar space. The WIM is nearly fully ionized, however the source of its ionization is not clearly recognized. Presumably it is caused by photons from O-type stars escaping from the HII regions to large distances from the galactic disk. The HII regions are created by extreme UV radiation from stars, which photoionize and heat the gas in their vicinity. Such regions can form in different conditions

(ionized by individual or associates of OB-type stars), which gives rise to different HII region classes summarized in Table B.2 (following Tielens 2005).

Table B.2: Physical parameters of HII regions.

Class	Size (pc)	Density (cm^{-3})	Ionized mass ($M_{\odot}$)	Number of ionizing stars
Hypercompact	3×10^{-3}	$\geq 10^6$	10^{-3}	1
Ultracompact	5×10^{-2}	$\geq 10^4$	10^{-2}	1
Compact	< 0.5	$\geq 5 \times 10^3$	1	1
Classical	10	$\geq 10^2$	10^5	few
Giant	5×10^1	30	$10^3 10^6$	10^2

The size of HII region can be estimated assuming the global ionization balance between the total recombination rate integrated over the source and the total ionizing luminosity $N_{Ly\alpha}$. The radius of HII region, with a constant density n is known as the Strömgen radius (Tielens 2005):

$$R_S \approx 1.2 \left(\frac{10^3 \text{cm}^{-3}}{n} \right)^{2/3} \times \left(\frac{N_{Ly\alpha}}{5 \times 10^{49} \text{photons s}^{-1}} \right)^{1/3} \text{pc}. \quad (\text{B.1})$$

Within the Milky Way, almost all ionized gas has a diffuse form, while most of $\text{H}\alpha$ emission comes from the HII regions. Distribution of the diffuse ionized gas (DIG) in the solar neighbourhood was studied by Berkhuijsen & Müller (2008), who proposed the model of DIG basing on the dispersion and emission measures determined in the direction of a sample of pulsars with known distances. Their results were in good agreement with the previous findings about the diffuse ionized gas in the Galaxy (e.g. Reynolds 1991b). The scale height of electron layers in the solar neighbourhood is about 1 kpc with temperature of about 8000 K. Berkhuijsen & Müller (2008) found also the inverse relation between the density within the clumps N_c and the filling factor f_V in the form of $f_V(N_c) = 0.011 N_c^{-1.20}$. The authors supposed that the relation is a consequence of almost constant averaged density along the line of sight, which is 0.018 cm^{-3} in the Milky Way. The result can support a hypothesis that the ISM was originated by turbulences, and has a hierarchical, fractal structure.

One of the ionized phases of the ISM is the hot ionized medium (HIM), hot ($\sim 10^5 - 10^6 \text{ K}$) and tenuous ($\sim 10^{-3} \text{ cm}^{-3}$) gas filling most of the Galactic volume. This phase is heated primarily by shocks driven by supernova explosions and stellar winds from associations of early-type stars.

APPENDIX C

Distribution of radio emission in galaxies

Observations of radio-emitting disks of face-on spiral galaxies revealed that the radio brightness can be well approximated by an exponential radial decline with a scale length L : (e.g. Beck 2015):

$$I(r) = I(0) \exp(-r/L) \quad (\text{C.1})$$

Typically, the scale length L is large and the radial decline of radio emission is more gradual than the optical emission, hence the radio emission extends further beyond the stellar disk. The observed radio emission results from two radiation processes and isolating the thermal component (free-free emission) is difficult, but can provide information on distribution of synchrotron component. Tabatabaei et al (2007b) separated free-free emission using a de-reddened $H\alpha$ map (corrected $H\alpha$ emission based on an extinction map derived from the IR Spitzer data) as a template for thermal emission. They applied the method to investigate the synchrotron emission of M33, and found its distribution more smooth than that of free-free emission. Moreover, the synchrotron scale length of M33 was about two times larger than the scale length determined for free-free emission.

The distribution of radio emission of edge-on galaxies is well described by two exponential components (Krause 2012):

$$I(z) = I_{thin}(0) \exp(-z/h_{thin}) + I_{thick}(0) \exp(-z/h_{thick}) \quad (\text{C.2})$$

Usually the models involving two exponential components fit data better than the models with one exponential or one Gaussian component. The typical mean value of the scale heights determined for five galaxies of different Hubble types and star-formation rates at 4.8 GHz are 300 ± 50 pc and 1800 ± 200 pc for the thin and thick disks, respectively (Krause 2012). However, the scale heights of radio emission for the starburst galaxy M82 (Adebahr et al. 2013), are 2 - 4 times smaller than the values obtained by Krause (2012). One of the most extended halos is observed in NGC 4631, where the local scale heights fluctuate highly and are significantly larger than the typical values. The mean scale heights for this galaxy are 370 and 2300 pc for thin and thick disks at 4.8 GHz, respectively (Mora & Krause 2013). It is believed that the scale heights of radio emission can be affected more by a strong tidal interaction than by star-formation efficiency within the galaxies.

APPENDIX D

Magnetic fields in galaxies

Magnetic fields are observed on a wide range of physical scales in the Universe, from sub-pc within stars to Mpc scales in radio galaxies and galaxy clusters. The total magnetic field strength of galaxies can be determined from their radio synchrotron emission, assuming equal contributions from the energy of magnetic field and the energy of relativistic particles, known as *energy equipartition* (Beck & Krause 2005). Thus, the total synchrotron intensity allows to estimate the total magnetic field strength B_{tot} . The average equipartition strength of total magnetic field in the spiral galaxies is about $10\mu\text{G}$ (Niklas 1995), while the local values within the spiral arms and bars are higher, up to $20 - 30\mu\text{G}$. The strength of magnetic field is statistically well related with surface density of SFR, which is described by a power-law with an index of 0.33 ± 0.03 (Chyży et al 2017). The relationship is observed for galaxies with different SFRs and morphological types.

The linearly polarized intensity can serve to estimate the strength and orientation of regular magnetic field in the sky plane. However, the polarization vectors in magnetized thermal plasma are subject to *Faraday rotation effect*. The angle $\Delta\chi$ by which the polarization vector is rotated is proportional to the square of the wavelength of observations λ^2 and proportional to the *rotation measure* (RM), defined as $\int N_e B_{||} dl$, where N_e is the density of thermal plasma, and $B_{||}$ is the magnetic field strength of the component parallel to the line of sight. Using multi-frequency observations, one can determine RM and correct the observed polarization angle of vectors. This step allows to estimate the strength and orientation of the regular magnetic field. The typical values of regular magnetic field strengths are in the range of $1 - 5\mu\text{G}$, and are usually at the strongest, $10 - 15\mu\text{G}$, in the regions between the optical spiral arms.

While the polarized intensity is a powerful tool for magnetic field studies, it does not allow to distinguish between the two possible scenarios: (1) regular fields of constant direction or (2) anisotropic magnetic fields. The rotation angle is sensitive to the sign of the field direction, thus, only the regular magnetic fields give rise to RM, and its pattern can be used to determine large-scale regular (coherent) magnetic field. The Faraday rotation is not the only process to influence polarimetric observations. Actually, there is quite a number of effects that can lead to decreasing the degree of linear polarization of synchrotron emission.

The spiral galaxies observed face-on show large-scale magnetic field patterns filling the

whole galactic disk. Some of the galaxies feature prominent magnetic spiral arms (e.g. NGC 6946) between the optical spiral arms, which presumably result from a large-scale dynamo. Such large magnetic field structures can be amplified and maintained in the galactic disk by an $\alpha\Omega$ – *dynamo* (mean-field dynamo), but a more efficient amplification of magnetic field can be attained through action of a small-scale dynamo (Beck et al. 1996). In other words, the mean-field dynamos can give a rise to the regular magnetic field structures, while small-scale dynamos, acting within turbulent gas, amplify the random magnetic field within the spiral arms.

The nearby edge-on galaxies usually show magnetic field lines parallel in respect to the galactic plane. Such a magnetic field structure is consistent with the expected projection of the spiral magnetic field observed in the galaxies seen face-on. At larger distances from the disk’s mid-plane, the vertical component of magnetic field extends beyond the optical emission. The star-forming regions in the disk are associated with radio emission spurs, which are channels where presumably the magnetic field is transferred (dragged) outwards by the galactic winds. In some edge-on galaxies, an X-shaped pattern of magnetic field is observed, especially in those with massive disks (eg. NGC 253, NGC 891, NGC 5775). The X-shaped fields are predicted by the models that combine field amplification by an $\alpha\Omega$ – *dynamo* with disk-halo outflows (e.g. Moss et al. 2010). On the other hand, the X-shaped morphology of magnetic field could be a consequence of disk flaring at large radii (e.g. Vollmer et al. 2015).

APPENDIX E

Numerical Modelling of Radio Emission from Galaxies

E.1 Description of code

The software for numerical modelling of radio emission from galaxies was written in C++. The object-oriented programming language allowed to organize the code as a hierarchy of objects representing thermal- and synchrotron-emitting medium. One of the primary goals was to provide software for numerical modelling, easy to maintain and giving enough flexibility to model sources of various geometries and sizes. All the modelling output files are stored as ascii files (maps and spectra), which can be readily modified, analysed and presented. The final results in the form of radio spectra and synthetic maps of radio emission were produced using Gnuplot and Python (e.g. matplotlib).

A three dimensional (3D) grid of the same number of cells and the same size along each axis (x,y,z) was used. Each of $N \times N \times N$ available cells was implemented by C++ class *GalPoint* (Figure E.1). There are 4 variables (properties) which define physical conditions within the cells. The synchrotron-emitting medium is characterized by the synchrotron intensity (*Intensity*) and synchrotron spectral index (*Alpha*), while the ionized medium is described by the gas density (*Density*) and temperature (*Temp*) (see class *GalPoint* in Figure E.1). The grid is implemented by class *Galaxy*, which inherits from class *GalPoint* describing the individual cells. The position of the modelled source within the grid can be rotated by two angles: inclination (*inclination*) and position angle (*pa*). All the values within the individual cells, as well as the position, can be set using the methods in class *Galaxy*. There are also two methods *thermalGas()* and *nonThermalGas()*, which serve to define the thermal and synchrotron components. Once the position of the source is determined (method *rotate(int,int)* of class *Point*), one can solve the radiative transfer equation along each line of sight for different frequencies (see Section 3.2).

E.2 Stability and precision of code

My numerical model of radio emission was tested in various ways. Apart from tests of particular functions/methods, I applied a few tests focusing on the physical interpretation of results, agreement with observations, and predicted effects.

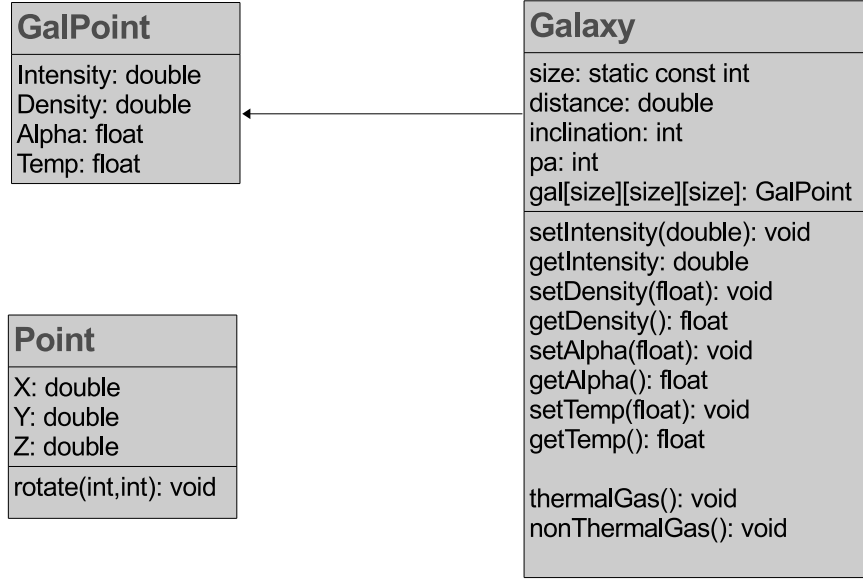


Figure E.1: C++ class diagram of NMREG.

E.2.1 Free-free emission

I first began with a simple model of HII region to verify results of modelling radio emission from ionized gas only, using the well-known HII region, *Orion A* to demonstrate quality and accuracy of the modelling.

The distribution of ionized gas associated with the model of *Orion A* adopted here involves the following simplifications:

- Geometry of a circular cylinder which symmetry axis coincides with the line of sight. The cylinder's length is equal to its diameter.
- The cylinder is filled with ionized gas of uniform temperature ($T_e = 10^4$ K) and density n_e throughout.

In order to model *Orion A* the average density of ionized gas $\langle n_e \rangle$ within the HII has to be known. The observed angular radius of *Orion A* is roughly $\theta \approx 10^{-3}$ radians, and taking its distance as 500 pc, I calculated that the linear diameter of this HII region is about 1 pc. The integrated radio spectrum of *Orion A* show a turnover at about 1 GHz and the flux density at frequency of 23 GHz is approximately 400 Jy (Goudis 1974). From the solution of the radiative transfer equation (see Eq. 1.9 in Chapter 1) for an optically thin medium ($\tau_\nu \ll 1$), the intensity $I_\nu = \tau_\nu B_\nu$. The flux density for a uniform source of simple geometry (circular cylinder) can be calculated as a $I_\nu \Omega_s$, while the solid angle Ω_s for a small source ($\theta \ll 1$ radian) is given by $\pi\theta^2$. Using the flux density of 400 Jy at 23 GHz and the source's angular radius of 10^{-3} radians, I obtained the intensity $I_{23GHz} = S_{23GHz}/\pi\theta^2 = 1.27 \times 10^{-18} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$. Subsequently, using the values of intensity I_{23GHz} and of the brightness B_{23GHz} , I calculated the optical depth $\tau_{23GHz} = 7.56 \times 10^{-4}$. From Equation 1.13 (see Chapter 1) describing τ_ν , I estimated that

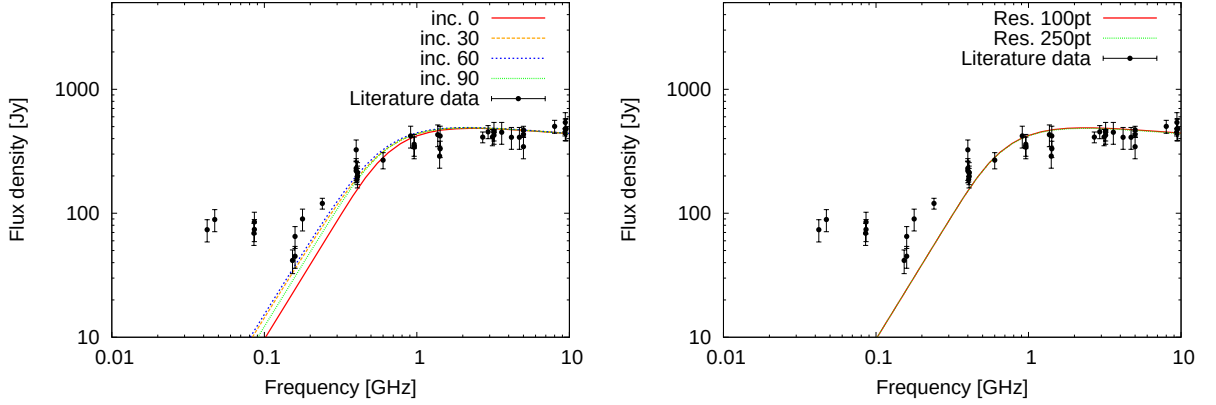


Figure E.2: (Left) Global spectra of the HII (Orion A-like) region seen at different inclination angles 0, 30, 60, and 90 degrees for a high-resolution model (250 points). (Right) Global spectra obtained for two different cell sizes: 100 and 250 points, for inclination angle 0 degrees.

at 23 GHz, the emission measure is $1.75 \times 10^6 \text{ pc cm}^{-6}$. Assuming that the length of the HII region is $s = 1 \text{ pc}$ and from the definition of $EM = \int_0^s n_e^2 ds$, I obtained $\langle n_e \rangle = 1.325 \times 10^3 \text{ cm}^{-3}$.

The above simple model of *Orion A* was implemented as a representative object for the purpose of testing a thermally radio-emitting source. I used a circular cylinder (both diameter and length of 1 pc) at distance of 500 pc, filled with ionized gas characterized by temperature of 10^4 K and gas density of $1.325 \times 10^3 \text{ cm}^{-3}$. Further on, I describe two tests to show stability of solutions in a wide range of frequencies, for different orientations of the modelled HII region with respect to the observer (inclination) and for different grid resolution (cell size).

The first test was designed to find any discrepancies between the results of numerical modelling of the above simple model of *Orion A* for two different cell sizes within the grid. The modelling was performed for two cases in which the diameter of the modelled HII region (of 1 pc) was represented by 100 points (cells) and 250 points (cells), respectively. In both the scenarios, I modelled radio emission from a circular cylinder (HII region) seen at different inclinations: 0, 30, 60, 90 degrees.

The global spectra (obtained for the high-resolution model involving 250 points) for different inclination angles are presented in Figure E.2 (left panel). The global spectra above 1 GHz, do not change with inclination angle, since they result from the thermal radio emission from an optically thin source. However, a strong dependence of viewing angle on global spectra can be seen at frequencies below 1 GHz, while for greater viewing angles there is a slightly weaker flattening of spectrum below the turnover. This effect can be easily understood as due to orientation of a circular cylinder of uniform medium with respect to the observer. In Figure E.3, I present the synthetic maps of thermal radio emission of the modelled HII region for the selected frequencies of 30, 150 and 1400 MHz and for different inclination angles of 0, 30, 60, and 90 degrees. The thermal radio emission at low frequencies (30 and 150 MHz) arises from optically thick regions, thus the synthetic maps do not show any significant changes in the intensity distribution (flux density/beam) with increasing inclination angle. Apart from the change of shape of the source due to different viewing angle, the values of intensity seem not to differ

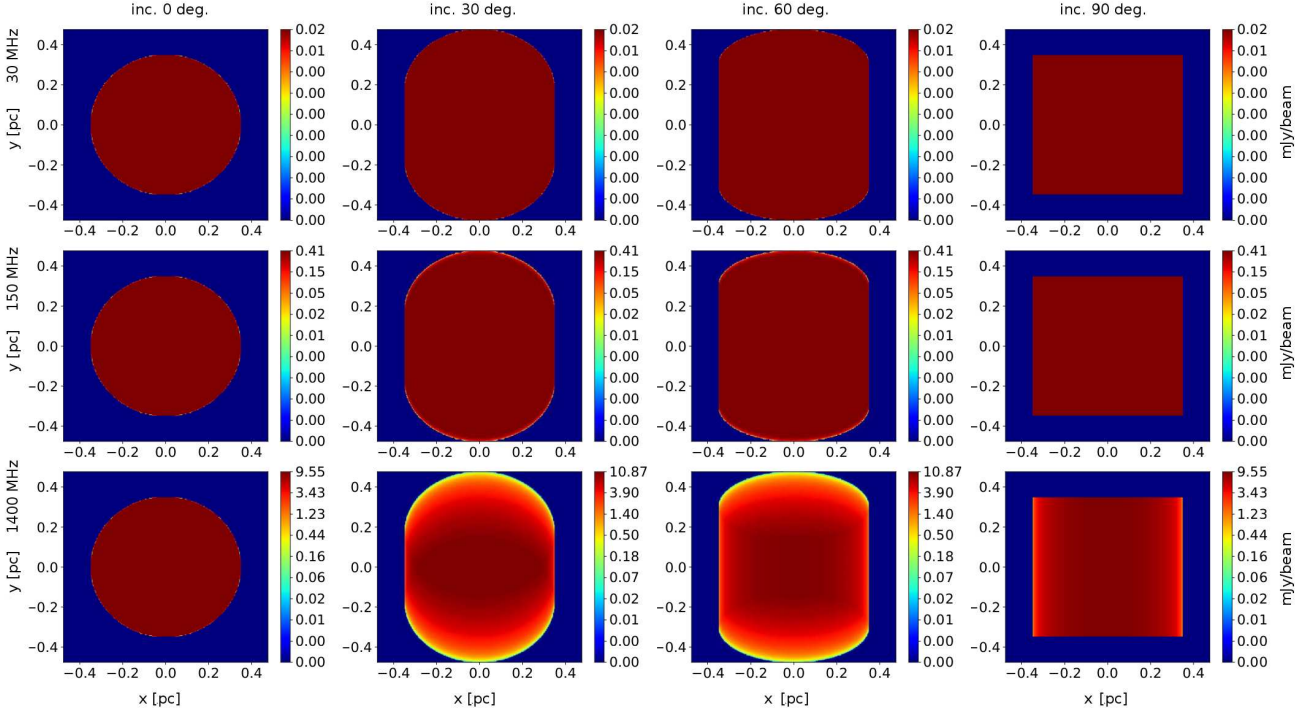


Figure E.3: Synthetic thermal radio emission maps of HII region, Orion A-like object: rows from top to bottom show results at 30 MHz, 150 MHz, and 1400 MHz, while columns from left to right present results for inclination angles: 0, 30, 60 and 90 degrees. The colour scale is in mJy/beam.

from the maximal intensity (0.02 and 0.41 mJy/beam at 30 and 150 MHz, respectively). In the case of circular cylinder with constant density of ionized gas for the inclination of 0 degrees, its radio emission arises from the regions with the same emission measure. Therefore, the radio emission in the all synthetic maps for inclination 0 degrees should have constant intensity for any frequency. The thermal radio emission above 1 GHz arises mostly from optically thin gas, while for greater inclination angles up to 60 degrees, it comes from the lines of sight with different emission measures (the effect can be seen in the maps at 1400 MHz at top and bottom edge of HII region in Figure E.3). When the modelled HII region is seen as edge-on (inclination 90 degrees) the mentioned effects are less visible and discrepancy between the intensity in the central parts of the maps and the intensity at the edges of maps is less pronounced.

Figure E.2 in the right panel depicts the global spectra obtained from modelling with two different cell sizes for the inclination angle of 0 degree. There is no evidence of the resulting global spectra being affected by different cell sizes. Otherwise, we would have noticed either horizontal or vertical shift of one of the spectrum. Despite of simplification of the applied model, the values of flux densities from modelling at frequencies above few hundred of MHz are in an excellent agreement with the observational data (Goudis 1974).

E.2.2 Synchrotron emission

In order to model radio emission from synchrotron-emitting medium, I used a similar circular cylindrical geometry of source as before, assuming for the purpose of tests that

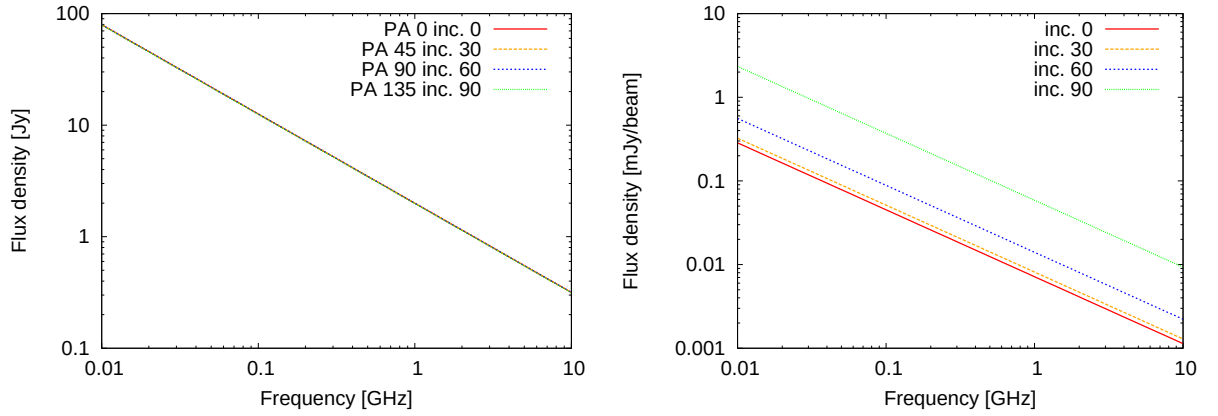


Figure E.4: (Left) Global spectra as seen for different inclination and position angles: 0, 45, 90, 135 degrees. (Right) Comparison of local spectra from the synchrotron disk's centre for inclination angles of 0, 30, 60 and 90 degrees.

a source has the radius of 15 kpc and height of 2 kpc, and is located at the distance of 3.25 Mpc, corresponding NGC 6946 (see Chapter 2). Moreover, the parameters of synchrotron-emitting medium (thermal medium is neglected) were adjusted so as to give the integrated flux density of about 1.4 Jy at 1.4 GHz, as in the case of NGC 6946, and the constant size of cells of 50 pc was assumed.

The synthetic maps of synchrotron radio emission at 1400 MHz obtained for 4 selected inclination angles and 4 different position angles are presented in Figure E.5. The total integrated flux density should be the same in each case, regardless of orientation of synchrotron disk since, no synchrotron absorption processes are taken into account (see Chapter 3). The proper numerical modelling of synchrotron emission should produce a family of global spectra for different orientation of disk, which we are not able to distinguish. The positive results of this test are presented in Figure E.4 (left panel). The modelled global spectra for 4 different orientations of synchrotron disk overlap each other, while this is not true of the local spectrum from the central parts of the synchrotron disk. The greater tilt of the synchrotron disk makes the line of sight to pass a longer path within the disk, leading to higher value of integrated intensity. These effects can be seen in local spectra presented in Figure E.4 (right panel). The obtained results are in concordance with predictions.

All performed tests of radio emission of thermal source (HII region) and synchrotron-emitting disk show that results are stable and accurate. The changes of model parameters (e.g. cell size, inclination, frequency) provide results, which are in very good agreement with analytical calculations and predictions.

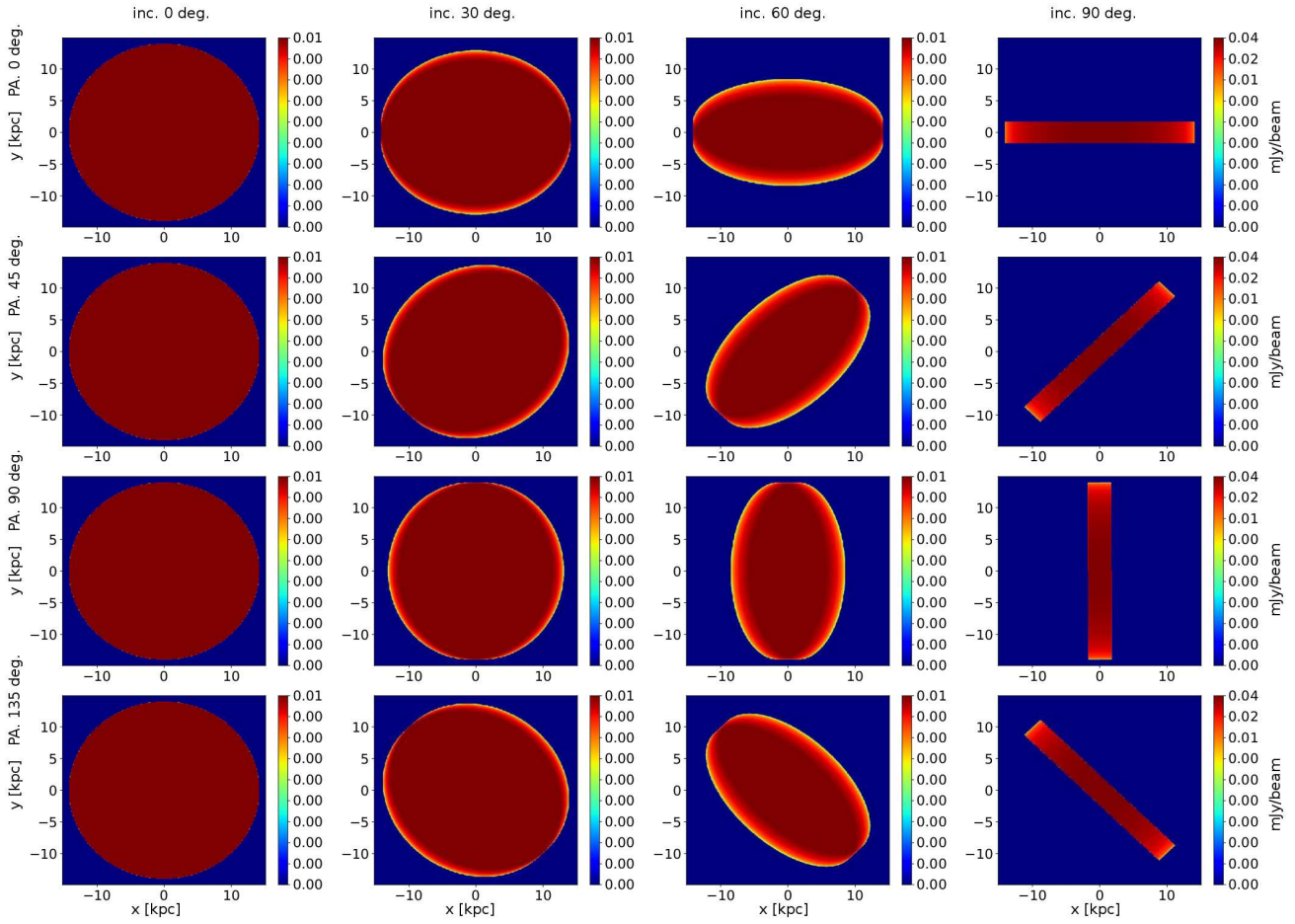


Figure E.5: Synthetic radio emission maps of a synchrotron disk at 1400 MHz, rows from top to bottom show results for different position angles: 0, 45, 90, 135 degrees; columns from left to right show results for inclination angles of: 0, 30, 60 and 90 degrees. The colour scale is in mJy/beam.

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