UNIVERSITY OF ZAGREB
FACULTY OF SCIENCE
DEPARTMENT OF PHYSICS

Nika Jurlin

OPTICAL IDENTIFICATION OF RADIO SOURCES IN THE XXL-SOUTH FIELD USING LIKELIHOOD TECHNIQUE

Master Thesis

Zagreb, 2017

SVEUČILIŠTE U ZAGREBU
PRIRODOSLOVNO-MATEMATIČKI FAKULTET
FIZIČKI ODSJEK

Nika Jurlin

OPTIČKA IDENTIFIKACIJA RADIO IZVORA U *XXL-SOUTH* POLJU KORISTEĆI TEHNIKU VJEROJATNOSTI

Diplomski rad

Zagreb, 2017

UNIVERSITY OF ZAGREB
FACULTY OF SCIENCE
DEPARTMENT OF PHYSICS

INTEGRATED UNDERGRADUATE AND GRADUATE UNIVERSITY
PROGRAMME IN PHYSICS EDUCATION

Nika Jurlin

Master Thesis

Optical identification of radio sources in the XXL-South field using likelihood technique

Advisor: Dr. Sc. Vernesa Smolčić, Associate Professor

Co-Advisor: Dr. Sc. Paolo Ciliegi, Research Astronomer

Master Thesis grade: ______________________

Committee: 1. ________________________

2. ________________________

3. ________________________

Master Thesis defence date: _______________

Zagreb, 2017

I would first like to thank my thesis advisor Dr. Sc. Paolo Ciliegi for his constant support during my internship in Bologna, and afterwards in the process of writing my Master's Thesis. He steered me in the right direction while still letting me give my own ideas and learn from my mistakes. I would also like to thank him for all the time he spent with me generously sharing his knowledge.

I thank Associate Professor Vernesa Smolčić, for giving me the opportunity to work in the field of astrophysics, and showing me how great and fulfilling this field of physics is. I also thank her for her valuable comments on this thesis.

I would like to thank Prof. Maja Planinić for showing me the passion she has for physics education and how creative the teaching could be. I also thank her for the guidance and valuable input on the Methodical part of my Master's Thesis.

I thank all my Professors, especially Prof. Damir Veža and Prof. Krešimir Pavlovski for their passionate way of teaching and believing in their students.

One of my biggest gratitudes goes to Dr. Sc. Jacinta Delhaize, Mag. Phys. Nikola Baran, Dr. Sc. Oskari Miettinen, Dr. Sc. Ivan Delvecchio and Mag. Phys. Mladen Novak for allways being there for me and helping me on my path.

Finally, I must express my very profound gratitude to my family for everything that 2 sentences can not describe. I especially would like to thank Milton, Bagi and Minou for their often silent support and encouragement.

This accomplishment would not have been possible without them.

Thank you.

Optička identifikacija radio izvora u *XXL-South* polju koristeći tehniku vjerojatnosti

Sažetak

Znanstveni dio diplomskog rada

Uvod

Astronomski radio izvori su objekti u svemiru koji emitiraju jake radio valove. Radio emisija dolazi iz širokog raspona procesa. Takvi objekti predstavljaju neke od najekstremnijih i energetskih izvora u svemiru.
Radio emisijom iz galaksija dominira sinkrotronska emisija od elektrona ubrzanih ili udarnim valom povezanim sa supernovama (i stoga povezanim s procesima stvaranja zvijezda) ili procesima koji su energizirani velikim nuklearnim objektom, kao što su Aktivne galaktičke jezgre (AGN) ili kombinacijom ta dva uzroka. Na osnovu samo emitirane radio emisije nije moguće utvrditi prirodu radio izvora. Stoga je identifikacija optičkih i rendgenskih odgovarajućih izvora radijskih izvora temeljni korak pri proučavanju prirode i evolucije radio izvora.
Cilj ovog rada je spojiti radio izvore sa optičkim izvorima, te proučiti njihova optička svojstva, otkrivena u *XXM-Newton XXL South* polju. XXL pregled neba pokriva dva ekstragalaktička područja od 25 deg^2. Glavni cilj projekta je pružiti dobro definiran uzorak klastera galaksija do crvenog pomaka, z $\approx$ 1 za kozmološke studije. Da bi se postigao ovaj cilj, mnogi pomoćni podaci dobiveni su u XXL polju, od radio do rendgenskog područja. Iskoristit ćemo ovaj izvanredan skup podataka kako bismo proučili optičke značajke radio izvora.

Korišteni podaci

Radio podaci korišteni u ovom radu dobiveni su pomoću *Australian Telescope Compact Array* na 2.1 GHz u *XMM-Newton Extragalactic Legacy Survey South (XXL-S)* polju [6]. Ukupna površina od $25\ deg^2$ pokrivena je sa rezolucijom od $\approx$ 4.7 arcsec. U katalogu izvora nalazi se ukupno 6293 objekta.

U tablici 2.1 možemo vidjeti primjer korištenog kataloga, dok na slici 2.1. vidimo položaje 6293 radio izvora.

Optički i blisko infracrveni (NIR) podaci dobiveni su pomoću nekoliko teleskopa/pregleda neba:

- *The VISTA Hemisphere Survey (VHS; PI: R. McMahon)*
- *The Blanco Cosmology Survey (BCS; Desai et al. 2012 [10])*
- *The Dark Energy Camera (DECam)*

Ovaj se katalog sastoji od 4 143 094 izvora i 15 različitih magnituda od ultraljubičastog do NIR područja.
Preklapanja radio i optičkih/NIR pozicija u svim područjima prikazana su na slikama 2.2 i 2.3.

Korištena tehnika

Za optičku/NIR identifikaciju 6293 radio izvora koristila sam tehniku vjerojatnosti [5, 7, 38]. Vjerojatnost je definirana kao omjer vjerojatnosti da je dani izvor prava optička identifikacija danog radio izvora, i vjerojatnosti da je taj isti objekt nevezani objekt iz pozadine (jednadžba 3.1), gdje je $q(m)$ očekivana raspodjela vjerojatnosti pravih optičkih/NIR identifikacija radio izvora kao funkcija magnitude, $f(r)$ je funkcija distribucije vjerojatnosti položajnih pogrešaka, a $n(m)$ je površinska gustoća objekata u pozadini, magnitude m [7].
Za svaki izvor usvojila sam eliptičnu Gaussovu raspodjelu za pozicijske pogreške s pogreškama u rektacenziji (RA) i deklinaciji (DEC) na radijskom položaju prijavljenom u radio katalogu i uz pretpostavku nesigurnosti optičke pozicije kao vrijednost od 0.3 arcsec.
Za procjenu $q(m)$ uzela sam polumjer od 3 arcsec, dobiven oduzimanjem očekivanog broja pozadinskih objekata ($n(m)$) od promatranog ukupnog broja objekata navedenih u katalogu oko položaja radio izvora.
Pouzdanost Rel_j, koja nam govori o ispravnosti identifikacije za objekt j dana je jednadžbom (3.2) [38], gdje je suma preko svih kandidata za ovaj izvor, dok je Q

vjerojatnost da je optički izvor koji odgovara radio izvoru svjetliji od granice magnitude optičkog kataloga ($Q = \int^{m_{lim}} q(m)dm$). Usvojena vrijednost za Q iznosi 0.8 [7]. Kada su dobiveni $q(m)$, $f(r)$ i $n(m)$, izračunala sam LR vrijednost za sve optičke izvore unutar udaljenosti od 3 arcsec od položaja radio izvora. Nakon što sam odredila LR za sve optičke kandidate, morala sam odabrati najbolju vrijednost praga za LR (L_{th}) kako bih mogla razlikovati lažne i stvarne identifikacije. Kao LR prag usvojila sam L_{th} = 0.2. Sa vrijednošću LR praga L_{th} = 0.2 i procjenom za $Q = 0.8$, svi optički izvori, koji odgovaraju radio izvorima, sa samo jednom identifikacijom (većina u dobivenom uzorku) i sa $LR > LR_{th}$ imaju pouzdanost veću od 0.5.
Primijenila sam ovu tehniku na 7 optičkih (g, r, i, z) i NIR (J, H, K) područja, što je rezultiralo u 7 kataloga. Spajanjem tih 7 kataloga dobila sam konačni katalog u kojem se nalaze i optičke i radio karakteristične veličine izvora.

Dobiveni rezultati

U svakom od prvotno dobivenih 7 kataloga, kada su za određene radio izvore postojala dva moguća odgovarajuća optička izvora sa $LR > LR_{th}$, zadržala sam samo optičke izvore s najvećom pouzdanosti, gdje je pouzdanost definirana kao u jednadžbi (3.2). Pri spajanju 7 kataloga u jedan veliki katalog sa radio i optičkim karakterističnim veličinama, kada sam za radio izvor, u glavnom katalogu, na raspolaganju imala dva (ili više) različitih odgovarajućih optičkih izvora (iz kataloga LR-a iz 7 različitih optičkih/NIR područja), pokušala sam pronaći područje u kojem su svi mogući odgovarajući optički izvori predloženi. U tom sam slučaju odlučila odabrati izvor na temelju pouzdanosti iz tog područja. Konačno, u slučaju kada nisam vidjela sve moguće odgovarajuće optičke izvore u jednom području, odlučila sam koristiti opću pouzdanost (tj. pouzdanost pridruženu svakom optičkom odgovarajućem izvoru izračunatom u različitim optičkim područjima).
Skraćeni prikaz rezultata nalazi se u tablici 4.1. Ondje možemo vidjeti broj radio izvora unutar *CCD* površine, broj optičkih izvora pronađenih u radijusu od 3 arcsec oko radio izvora i broj izvora sa pouzdanom optičkom identifikacijom za svako područje. Od ukupno 6293 radio izvora, njih 6176 nalazi se unutar *CCD* površine. Ukupno 4738 radio izvora ima odgovarajuće optičke izvore, te se oni sada nalaze u novom katalogu sa svojim odgovarajućim optičkim izvorima, magnitudama i udaljenostima

između radio i optičkih/NIR pozicija.
Slike 4.1, 4.2 i 4.3 prikazuju primjenu tehnike vjerojatnosti za optička i NIR područja, gdje crna puna linija predstavlja opaženu raspodjelu magnitude svih optičkih/NIR izvora prisutnih u odgovarajućem području, u radijusu od 3 arcsec oko svakog radio izvora. Plava iscrtkana linija predstavlja očekivanu raspodjelu pozadinskih objekata na istoj površini. Razlika između te dvije raspodjele (crne i plave) jest očekivana raspodjela magnituda optičkih/NIR izvora koji odgovaraju radio izvorima te je prikazana crvenom bojom.

Optička svojstva radio galaksija

Distribucija spektroskopski dobivenog crvenog pomaka prikazana je na slici 5.1.
Vidimo kako se otprilike 90% izvora nalazi na crvenom pomaku $z \leq 1$ sa malenim brojem izvora koji se protežu do crvenog pomaka $z \approx 3$. Broj radio izvora sa odgovarajućom optičkom identifikacijom podijeljen u određene intervale crvenih pomaka prikazan je u tablici 5.1.
Na slikama 5.2. i 5.3 s lijeva na desno možemo vidjeti distribuciju radio toka za cijeli radio uzorak (crni histogram; na svakoj slici jednakog značenja) i za 4738 radio izvora sa pouzdanom optičkom identifikacijom (narančasti histogram); 1056 radio izvora za koje imamo podatke o spektroskopski dobivenom crvenom pomaku (narančasti histogram); 1056 radio izvora za koje imamo podatke o spektroskopski dobivenom crvenom pomaku i i_{BCS} magnitudi (narančasti histogram); 1056 radio izvora za koje imamo podatke o spektroskopski dobivenom crvenom pomaku i K magnitudi (narančasti histogram). Iz njih možemo zaključiti kako su većina neindetificiranih radio izvora, izvori slabijih magnituda.
Studije distribucija magnituda i boja optičkih izvora koji odgovaraju radio izvorima mogu nam reći nešto o prirodi radio izvora slabijih magnituda. Na slikama 5.4 i 5.5 možemo vidjeti distribuciju magnituda u određenim optičkim i NIR područjima. Crnim je histogramom prikazana distribucija magnituda cijelog optičkog uzorka, dok je narančastim histogramom prikazana distribucija magnituda optičkih izvora koji odgovaraju radio izvorima.
Možemo zaključiti kako je distribucija magnituda optičkih izvora koji odgovaraju radio izvorima plosnatija od one globalne, što ukazuje na značajni udio radio izvora

povezanih s relativno svijetlim optičkim galaksijama/AGN-ovima. Zbog toga što se maksimum distribucije radio izvora poklapa s maksimumom ukupne distribucije, možemo zaključiti da je relativno nizak postotak identifikacije rezultat ne toliko duboke rubne magnitude optičkih/NIR podataka.

Na slikama 5.6, s lijeva na desno, prikazani su I-K boja kao funkcija radio toka, I magnitude i radio-optičkog omjera, R za 3 intervala crvenog pomaka, kao što je naznačeno na slikama. Radio-optički omjer, R, definiran je u jednadžbi (5.1), gdje je S radio tok, a I prividna magnituda. Dok nema primjetne korelacije između I-K i radio toka, korelaciju primjećujemo između I-K i I magnitude te radio-optičkog omjera, R. Sličan uzorak za optički svjetlije magnitude da imaju crvenije I-K boje već je bio uočen i u prijašnjim radovima [7, 29]. Iz slika 5.6 također primjećujemo korelaciju sa crvenim pomakom. Kako idemo od intervala crvenog pomaka 0-0.5 (plave točke na slici 5.6) do 0.5-1.0 (narančaste točke na slici 5.6) radio izvori postaju crveniji te imaju veći R. Taj bi uzorak mogao sugerirati da su izvori bez spektroskopski određenog crvenog pomaka (svijetlo sive točke na slici 5.6), upravo izvori koji se nalaze na velikim crvenim pomacima, od kojih bi neki mogli biti klasificirani kao Ekstremno Crvene Galaksije (engl. *Extremely Red Galaxies, ERO*), odnosno izvori sa I-K > 4 (drugi desni plot na slici 5.6). Na osnovu rezultata prikazanih na slikama 5.6 možemo zaključiti kako su radio izvori povezani sa galaksijama koje stvaraju zvijezde (plavije galaksije i manji R) vjerojatno galaksije manjeg crvenog pomaka, dok su radio izvori povezani sa galaksijama ranog tipa (crvenije boje i veći R), objekti većeg crvenog pomaka.

Metodički dio diplomskog rada

Uvod

Astronomija je jedna od najstarijih grana znanosti. Ljudi su se oduvijek pitali o nebeskim tijelima i pojavama koje ih okružuju. Uz vjerske, političke i tehnološke poteškoće, kozmološke su se teorije mijenjale od geocentričnih do heliocentričnih, te smo naposlijetku došli do suvremene astronomije i teorije Velikog praska. Unatoč toliko dugom prisustvu astronomije u ljudskim životima, istraživanja u području edukacije u astronomiji tek su na početku.

Sadržaji vezani uz astronomiju u hrvatskim školama

U Hrvatskoj tek u rijetkim srednjim školama postoji izborna nastava astronomije. Osnovno znanje vezano uz temeljne pojmove astronomije, poput Sunčevog sustava, astronomskih pojava i svemira, učenici stječu kroz predmete poput kemije, geografije, biologije, matematike, a poglavito fizike. U Hrvatskoj, ali i izvan nje, učenicima nedostaje razumjevanje osnovnih pojmova i koncepata za koje bi se mnogi složili da spadaju u opću kulturu.

U Hrvatskoj, očekivana učenička postignuća iz svih predmeta, pa tako i fizike, određena su Nacionalnim okvirnim kurikulom [12].

Fizikalni koncepti, pretkoncepcije i miskoncepcije

Učenici formiraju svoje koncepte pod utjecajem izravnog iskustva, kulturnog okruženja i formalnog obrazovanja. Samim time se, kao što možemo i primjetiti, neke ideje vezane uz fizikalne pojave formiraju i prije učenja fizike u školi. To su tzv. pretkoncepcije: spontano formirani koncepti, koji se najčešće ne podudaraju s fizikalnim konceptima. Oni se formiraju na temelju iskustva i pojednostavljenog zaključivanja. Tako učeničke alternativne koncepcije možemo podijeliti na pretkoncepcije i hibridne koncepcije, koje se javljaju kao spoj pretkoncepcija i učenja.

Miskoncepcije obuhvaćaju sve učeničke koncepte koji nisu u skladu sa znanstvenim spoznajama

Zadaća profesora fizike je između ostaloga promijeniti učeničke pretkoncepcije pa tako i miskoncepcije koje nisu u skladu s fizikom. Kako bi uspjeli u tome, postojeća koncepcija mora se pokazati nezadovoljavajućom, te nova ideja mora biti razumljiva, uvjerljiva i plodonosnija od stare.

Konceptualna promjena jest kognitivni proces u kojem je naglašena promjena ideja kroz proces učenja. Nastavnik ju potiče, no učenik je onaj koji ju provodi. Prvi korak je dakako identifikacija pretkoncepcija/miskoncepcija, a zatim slijedi primjena neke od tehnika induciranja konceptualne promjene poput:

- tehnike kognitivnog konflikta

- supstitucije koncepata
- metode analogija
- Sokratskog dijaloga

Kognitivni konflikt i Sokratski dijalog predstavljaju intelektualni izazov za učenike, što može biti poticajno, ali i frustrirajuće. S druge strane, supstitucija koncepata i metoda analogija su blaže i lakše za učenike, no i dalje je najbolje kombinirati metode.

Istraživanja na području edukacije iz astronomije

Mnoga su istraživanja provedena na temu edukacije iz astronomije, pritom se osvrčući na učeničko razumijevanje, ali i očekivanja učitelja u vezi učeničkog razumijevanja koncepata iz astronomije.
Ta su istraživanja ukazala na velik broj učeničkih miskoncepcija, poput one koja kaže da je uzrok izmjene godišnjih doba u promjenjivoj udaljenosti između Zemlje i Sunca (da je Zemlja bliže Suncu ljeti, a dalje od njega zimi). Kod studija koje su se bavile miskoncepcijama učitelja u vezi razumijevanja koncepata iz astronomije kojima raspolažu njihovi učenici, pokazalo se kako profesori u prosjeku dobro predviđaju učeničko znanje na početku nastave, no uvelike precijenjuju učeničko znanje na kraju.
Iz rezultata ovih istraživanja može se zaključiti kako profesori nisu svjesni učeničkih miskoncepcija i njihovih mogućnosti da usvoje neki koncept. Stoga se profesori ne odlučuju posvetiti više vremena usvajanju nekog koncepta ili primjeni drugog pristupa. Istraživanje u hrvatskim srednjim školama ukazalo je slabo poznavanje temeljnih pojmova i koncepata iz područja astronomije.
Test koji je bio proveden nad učenicima prvih i četvrtih razreda triju srednjih škola sastojao se od 30 pitanja, od čega je 23 pitanja višestrukog izbora i 7 pitanja otvorenog tipa [26].
Provedbom ovog testa potvrđene su sljedeće miskoncepcije:

- Poistovjećivanje sile teže s akceleracijom sile teže
- Na Mjesecu nema gravitacije
- Povećanje tangencijalne brzine planeta, kada se on nalazi bliže Suncu, dolazi od povećanja gravitacijske sile kojom Sunce djeluje na planet

- Godišnja doba ovise o udaljenosti Zemlje od Sunca
- Plima i oseka nastaju zbog Mjesečeva magnetskog polja, koje djeluje na morsku vodu
- Kemijski sastav zvijezda može se odrediti analizom kometa i meteora koji padnu na Zemlju
- Crvene zvijezde imaju veću temperaturu od plavih zvijezda
- Period Mjesečeve rotacije oko Zemlje je 24 sata

Implikacija za nastavu fizike i zaključak

Kako vani, tako i u Hrvatskoj, profesori se često susreću s učeničkim miskoncepcijama. U nastavi astronomije, odnosno nastavi fizike i ostalih prirodoslovnih predmeta, učenici se tijekom cijelog osnovnoškolskog i srednjoškolskog školovanja susreću sa pojmovima i konceptima iz astronomije. Usprkos tome, i dalje veliki broj učenika dijeli miskoncepcije. Kao one najustaljenije možemo izdvojiti uzrok izmjene godišnjih doba i plime i oseke [26].

Astronomija i astrofizika važne su grane znanosti. U današnje doba, kada tehnologija napreduje svakim danom, nedopustivo je da učenici iz srednjih škola ne izlaze sa barem dobro pokrivenim konceptima i činjenicama vezanim uz osnovne astronomske ideje.

Prvi i osnovni korak k ovom cilju bio bi upoznavanje profesora s učeničkim miskoncepcijama. U kombinaciji sa zamjenom predavačkog stila nastave sa interaktivnom istraživački usmjerenom nastavom, te aktivnim uključivanjem učenika u tijek nastave, brojne se miskoncepcije mogu ispraviti.

Ključne riječi: astrofizika, radio izvori, optički izvori, tehnika vjerojatnosti, miskoncepcije, astronomija

Optical identification of radio sources in the XXL-South field using likelihood technique

Abstract

In this Master's Thesis I present optical identification of the 6293 radio sources detected in the 2.1 GHz deep radio survey down to a median rms of $\sigma \approx 41\mu$Jy/beam obtained with Australia Telescope Compact Array (ATCA) in the XMM-Newton Extragalactic Legacy Survey South (XXL-S) field. For the optical identification of these 6293 radio sources, I used the likelihood ratio (LR) technique, giving a fraction of identification around 77% (4738/6176). Moreover, we find that a significant fraction of radio sources is associated to relatively bright galaxies while the majority of the radio sources without an optical/NIR counterpart are faint radio sources. On the basis of the colour properties and the spectroscopic information, I classify the sources as star forming or early type galaxies.

As methodical part of my Thesis, I give a short summary of the research conducted in the field of astronomy education in high schools all over the world. I emphasize on misconceptions students have and what would, in my opinion, be the best way to achieve conceptual change.

Keywords: galaxies, radio sources, optical sources, likelihood ratio technique, astrophysics, astronomy, education, misconceptions

Contents

1 Introduction

1.1 Astronomical radio sources and thesis overview

Astronomical radio sources are objects in the Universe that emit strong radio waves. Radio emission comes from a wide variety of processes. Such objects represent some of the most extreme and energetic sources in the Universe.

In the year 1932, American physicist and radio engineer Karl Jansky detected radio waves coming from an unknown source in the center of our galaxy. The first radio sky survey was conducted by Grote Reber and was completed in 1941. In 1942 a group of British army radar operators detected for the first time bursts of radio energy from the Sun. In the 1970s, some stars in our galaxy were found to be radio emitters, one of the strongest being the unique binary MWC 349. Some of the more notable radio galaxies are Centaurus A and M87.

During the last 3 decades many radio surveys have been obtained, every time increasing the area covered, as well as the flux sensibility, thus sampling larger and larger volume of the Universe (the median redshift of radio galaxies is $z \approx 1$, [8]). The most straightforward information that can be derived from extragalactic radio sky surveys are the radio source counts. Radio source counts can be used to study the cosmological evolution of active galaxies (e.g. [16, 21, 40]) as well as their global properties. Radio emission from galaxies is dominated by synchrotron emission from electrons accelerated either by shock wave associated with supernovae (and hence related to star formation processes), by processes energized by massive nuclear object, such as Active Galactic Nuclei (AGN) or by the combination of the two. On the basis of the radio emission only, it is not possible to identify the nature of the radio sources. Therefore, the identification of the optical and X-ray counterpart of the radio sources is a fundamental step in order to study the nature and evolution of the radio sources. In fact, the scientific return from large radio surveys is enormously increased if the optical counterparts of the radio sources, as well as their nature (as AGN, starburst galaxy, etc.) can be identified and their redshift distribution measured.

The aim of this thesis is to study the optical properties of the radio sources, detected in a XXM-Newton XXL South field, obtained with the Australian Telescope Compact Array.

The XXL survey covers two extragalactic areas of $25\ deg^2$, using 10 ks XMM observations down to a point-source sensitivity of $\approx 5 * 10 - 15 erg/s/cm^2$ in the $[0.5 - 2]keV$ band. The main goal of the project is to provide a well defined sample of galaxy cluster up to redshift ≈ 1 for cosmology studies. In order to reach this goal, many ancillary data have been obtained in the XXL fields, from the radio to the X-ray bands. We will make use of this extraordinary data set in order to study the multiwavelength properties of the radio sources.

In first three subsections I give an overview of the classification of Starburst galaxies, Active Galactic Nuclei, AGN and how to discriminate between the two of them.

In section 2 I give a short overview of the radio, optical and near infrared (NIR) data used in this work.

Section 3 describes the technique I used to find optical and NIR identifications of radio galaxies, for which results are described in the section 4.

In section 5 I discuss the optical properties of the radio galaxies on the basis of magnitude distributions and colour diagrams, where I also used spectroscopic redshift provided by Dr. Sotiria Fotopoulou.

Finally in section 6 short summary is presented.

1.2 Starburst galaxies

Starburst galaxies are galaxies that are observed to be forming stars at an unusually fast rate, from tens to hundreds solar masses per year. At these high levels of star formation it is estimated that the supply of gas and dust within the galaxy would be exhausted within about 10^8 years, meaning that these episodes of intense star formation must have started relatively recently and will end in the not too distant future.

The areas of high activity can be spread throughout the galaxy, but most star forming regions are observed in a small area around the nucleus. Although the mechanism is still poorly understood, it is thought that the star formation is triggered by tidal interactions between galaxies passing close to one another, galaxy mergers, or due to the presence of a galactic bar, all of which result in the accumulation of substantial amounts of gas and dust in the central regions of the galaxy. Although hidden from us at optical wavelengths by the enshrouding dust, massive stars are formed out of the available gas. They emit copious amounts of ultraviolet wavelengths which is absorbed by the surrounding dust and reemitted at infrared wavelengths, making starburst galaxies among the most luminous infrared objects in the Universe. The radio emission is transparent to the dust, it is not obscured. Because of this, the observations in the radio band are very important for understanding the process of star forming. Ironically, it is the rapid rate of star formation that ultimately terminates the period of starburst. Supernovae explosions and stellar winds from the newly formed massive stars can be sufficient to sweep the gas from the galaxy thereby halting all further star formation.

Starburst galaxies have also been observed in the early Universe and appear to be more prevalent than they are now. These galaxies located about 12 billion light years distant, appear to have the same characteristics as the nearby starbursts and indicate that galaxy interactions were much more common in the past.

1.3 AGN

Many galaxies have very bright nuclei. Their nuclei is so bright that the central region can be more luminous than the remaining galaxy light. These nuclei are called Active Galactic Nuclei (AGN). Much of the energy output of AGNs is of a non-thermal (non-stellar) type of emission, with many AGN being strong emitters of X-rays, radio, ultraviolet and optical radiation. AGN can vary in luminosity on short (hours or days) timescales. This means that the light or energy emitting source must be of order light hours or light days (respectively) in size. It gives us clues to the energy mechanism.

Carl Seyfert discovered the first class of AGN, that are now named after him. The nuclei of Seyfert galaxies display emission lines. Type 1 Seyfert galaxies have both narrow and broadened optical spectral emission lines. The broad lines imply gas velocities of 1000 – 5000 km/s very close to the nucleus. Seyfert type 2 galaxies have narrow emission lines only (but still wider than emission lines in normal galaxies) implying gas velocities of 500-1000 km/s. These narrow lines are due to low density gas clouds at larger distances (than the broad line clouds) from the nucleus. Seyfert galaxies comprise 10% of all galaxies.

As well as Seyferts, other galaxies are also classified as AGN. These include radio galaxies, quasars, blazars and LINERs.

Radio galaxies, as their name implies, are strong emitters of radio emission. These are elliptical galaxies with nuclear radio emission, often accompanied by single or twin radio lobes that can be Mpc-sized. The radio emission is non-thermal, due to fast moving electrons that spiral in magnetic fields, producing synchrotron emission. Sometimes the radio lobes and nuclear radio emission are joined by narrow radio jets.

Quasars are the most luminous AGN. The spectra of quasars are similar to Seyferts except that stellar absorption features are weak or absent, and the narrow emission lines are weaker relative to broad lines as seen in Seyferts. Blazars are highly variable AGN that do not display emission lines in their spectra. Low Ionisation Nuclear Emission-line Region galaxies (LINERs) are very similar to Seyfert 2 galaxies, except the low ionisation lines, like $[OI]$ and $[NII]$, are quite strong.

AGN are thought to be powered by centrally located, supermassive black holes. The central regions of all AGN are thought to be similar and are explained by the Unified Model of AGN. The variation in AGN properties is thought to be related to the line of sight we have into the central region of the AGN. As can be seen in Figure 1.1, Unified Model of AGN shows a central supermassive black hole surrounded by a gaseous accretion disk of approximately a few light days across.

Moving outwards from the centre of the AGN fast moving gas clouds exist at a distance 100 light days. That region is known as the 'broad line region' which produces the broad emission lines seen in some AGN spectra. Continuing outwards, at 100 light years in diameter, we can see torus of colder gas. It is optically thick, and if viewed edge-on, will block out the accretion disc and broad line region from view. At a distance of 1000 light years, the 'narrow line region' exists. It is comprised of small, low density gas clouds moving at lower velocities than the broad line region. It is these clouds that are energised (usually close to the direction of the radio jets) and they produce the narrow emission lines seen in some AGN spectra. Radio (synchrotron) emission is produced in many AGN, collimated into jets and propagates in a direction that is perpendicular to the plane of the accretion disc. These radio jets are prominent in many radio galaxies and can be as large as several Mpc in size. Many jets end in broadened and diffuse radio lobes. When the molecular torus is viewed edge-on, the black hole, accretion disk and broad line region are hidden. When spectra are taken, we see emission lines from the narrow region only, as well as some

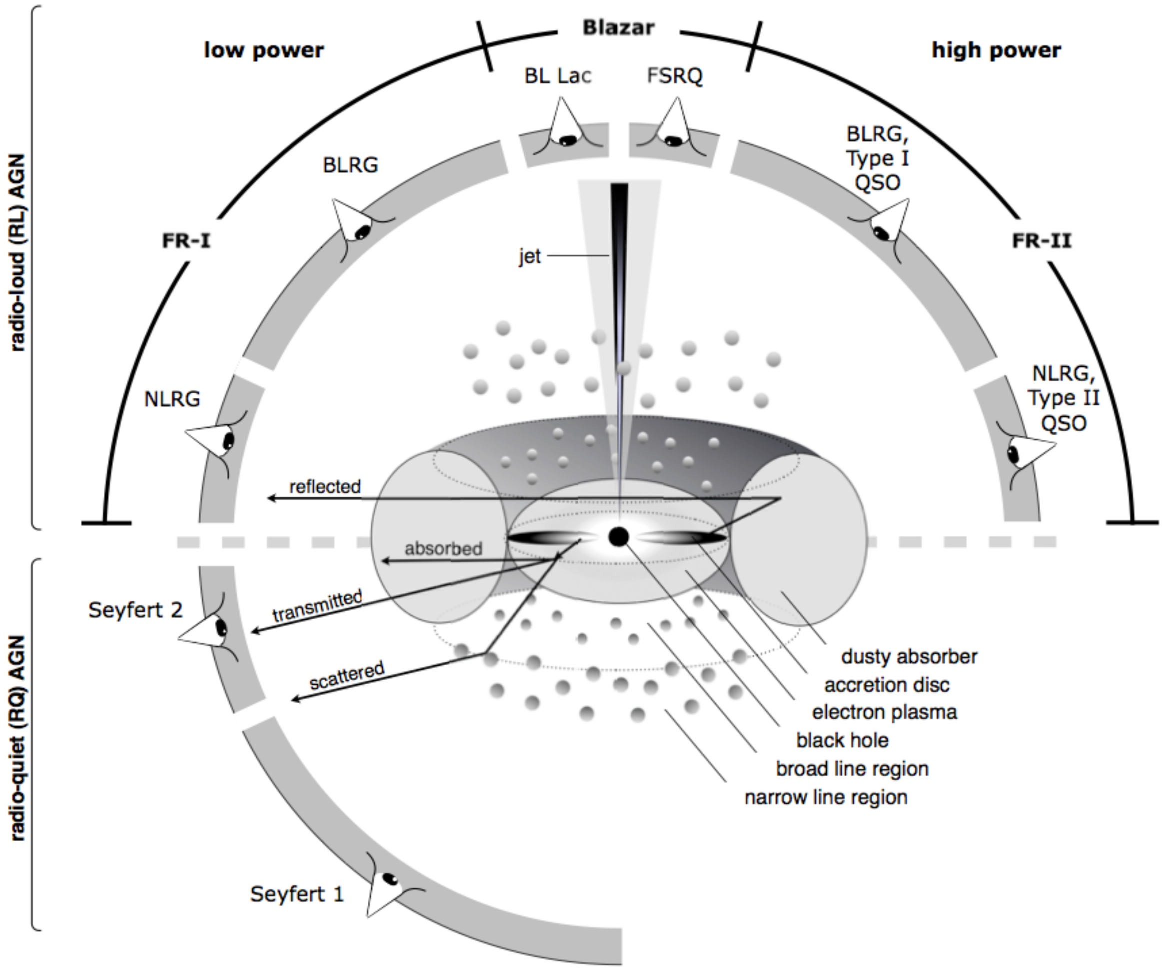

Figure 1.1: Sketch of the basic ideas of the unified AGN model. Credit: Beckmann & Shrader (2012) [3, 43]

infrared emission from the torus itself. In this case we detect Seyfert 2, (narrow line) radio galaxies and quasars. If our line of sight allows us to view into the central region – for example, the torus is tilted at 45 degrees – both broad and narrow lines are visible. In this case we detect Seyfert 1, broad line radio galaxies and quasars.

If we can look directly into the torus (if it is tilted at 90 degrees to our line of sight), we look face-on at the nucleus and jets. Radiation from the jet moves close to the speed of light and can be variable on periods from hours to days. This emission can dominate any narrow or broad lines and the spectra will appear featureless. In this case blazars, BL Lacs or Optically Violent Variables (OVVs) are detected. The radio-loud AGN population and their radio emission is linked to the presence of bipolar outflows of relativistic jets. The main mechanisms proposed so far are synchrotron radiation from mildly relativistic mini-jets, thermal cyclo-synchrotron emission by low-efficiency accretion flow, or thermal free-free emission from the X-ray heated corona or wind. If the AGN is able to form a bipolar outflow of relativistic plasma, then its radio emission becomes comparable to or even stronger than the emission observed in the other energy bands. The presence, or lack, of relativistic jets is at the basis of the radio-loud and radio-quiet dichotomy. Only 10% of the AGN population is radio-loud, while in the large majority the radio emission is a negligible part of the bolometric luminosity. The latter are termed radio-quiet AGN and their radio luminosity at 1.4 GHz does not exceed 10^{23} W/Hz (e.g. [9]). Although the radio emission is a very marginal part of the energy released by radio-quiet AGN, it represents a unique way to investigate the high energy particle accelerators. Understanding the origin of the radio emission from radio-quiet AGN is not trivial. Usually radio-quiet AGN are hosted in late-type galaxies where star formation is responsible for the majority of the radio emission. A significant fraction of the radio emission in radio-quiet AGN comes from processes related to the stellar evolution, like synchrotron emitting cosmic rays accelerated by supernovae, and thermal free-free radiation from the ionized gas in star forming regions. The fact that the tight radio/far infrared (FIR) correlation found for star-forming galaxies (SFG) holds in radio-quiet AGN, supports the idea that the bulk of the radio emission in radio-quiet AGN is related to stellar processes, while the agreement is poor in radio-loud AGN due to the presence of relativistic jets (e.g. [25]).

1.4 Discriminating between Starburst and AGN

In order to resolve Starburst and AGN galaxies in the radio regime, observations at other wavelengths are required. The commonly adopted and well – calibrated tool for resolving Starburst galaxies from low-luminosity AGNs (Seyfert and LINERs) is the optical spectroscopic diagnostic diagram [2], that is based on two emission line flux ratios ($[OIII5007] = H\beta$ vs. $[NII6584] = H\alpha$ (hereafter BPT diagram; see also [30, 39]). This diagnostic tool has been extensively used in the past for a successful separation of local SF and AGN galaxies [4, 17, 24, 32, 35]. Since spectroscopic observations are very expensive in terms of telescope time, especially when large numbers of faint objects need to be observed, alternative methods for the separation of SF from AGN galaxies, that eliminate the need for spectroscopy, have to be invoked.

An example of an alternative method can be found in Smolčić et al., 2008. [36]

The main idea of their method was drawn from the findings that the overall Near Ultra Violet (NUV) to Near Infra- Red (NIR) spectral energy distribution (SED) of galaxies is a one-parameter family, and that spectral diagnostic parameters, such as line strengths, appear to be well correlated with the overall galaxy's SED [24, 35]. In particular, Smolčić et al. (2006) [35] have found a tight correlation between rest-frame colours of emission-line galaxies and their position in the BPT diagram. This correlation provides a powerful tool for resolving SF from AGN galaxies using only photometric data, i.e. rest-frame colours, and they utilized it as the key of their rest-frame colour based classification method. Based on spectral line properties they separated the local sample into three classes of objects: AGN, star-forming galaxies and composite objects, where the latter are considered to have a comparable contribution of both star formation and AGN activity. The application of this method the the radio sources detected in the COSMOS-VLA survey [34] shows that the sub−mJy radio population is a mixture of about 30-40% of star forming galaxies and 50-60% of AGN [36].

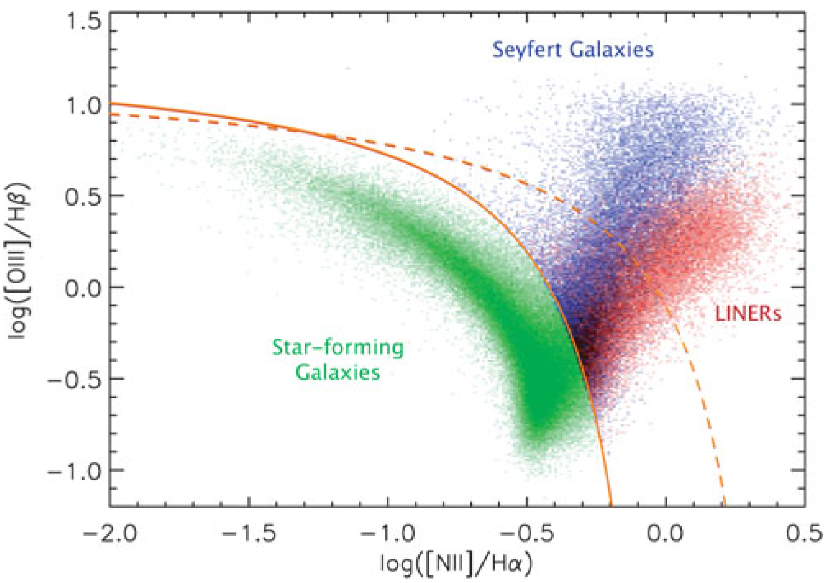

Figure 1.2: Example of the BPT diagram. This figure reveals the spread of emission-line galaxies from the Sloan Digital Sky Survey (SDSS) on the line ratio diagnostic diagram of Baldwin, Phillips & Terlevich. Credit: [42]

2 Data

2.1 Radio data

The radio data used in this thesis were obtained with the Australian Telescope Compact Array (ATCA) at 2.1 GHz in the XMM-Newton Extragalactic Legacy Survey South (XXL-S) field [6]. A total area of 25 deg^2 has been covered with a resolution of ≈ 4.7 arcsec and a median rms noise of $41 \mu Jy/beam$. A total of 6349 radio components above 5 σ are included in the component catalogue. Ninety-nine of these components were merged together into 43 multiple-component radio sources, resulting in a total of 6293 radio sources in the source catalogue, 25.9% of which were resolved. In table 2.1 we report an example of the entries of the radio catalogue, while figure 2.1 shows the RA and DEC distributions of the 6293 radio sources.

This catalogue consists out of 17 columns.

ID	RA_wc(deg)	Dec_wc(deg)	...	...	rms(mJy/b)	S_p(mJy/b)	...	S_int(mJy)	...	SNR	Res	MC	DC_size(arcs...	DC_size_err(...	Freq_eff(GHz)	Complex
1	354.0505	-52.60612	..	..	0.658	1804.1936	..	1849.36...	..	2741.9...	0	0	0.	0.	1.8382	1
4	348.36237	-53.72467	..	..	0.567	1168.3644	..	1189.19...	..	2060.6...	0	0	0.	0.	1.844	1
5	350.52832	-54.75848	..	..	0.382	692.2475	..	1210.82...	..	1812.1...	1	0	4.123	0.344	1.8046	1
7	353.68698	-52.85537	..	..	0.475	688.1746	..	1168.62...	..	1448.7...	1	0	3.98	0.346	1.8175	1
3	350.25092	-54.04277	..	..	0.164	351.568	..	353.5314	..	2143.7...	0	0	0.	0.	1.8007	0

Table 2.1: 2.1 GHz radio source catalogue of the 25 deg^2 XMM-Newton Extragalactic Legacy Survey South (XXL-S) field, obtained with Australian Telescope Compact Array

Column 1 lists the identification (ID) number of each source.

Columns 2 and 3 list the flux-weighted RA and Dec, respectively, of each source in degrees.

Columns 4 and 5 contain the RA and Dec uncertainties as calculated by blobcat (σ_{RA} and σ_{Dec}), in arcseconds. For an explanation of how these are calculated, see Section 2.6 in Hales et al. (2012) [15].

Column 6 is the local rms noise σ_{rms} in mJy/beam.

Columns 7 and 8 list the peak flux density (S_p) corrected for bandwidth smearing and the uncertainty in S_p (σ_{Sp}), respectively, in mJy/beam. The uncertainty σ_{S_p} is defined as the quadrature sum of the absolute calibration error, the pixellation uncertainty, and the local rms noise. Multiple-component sources have $S_p = -99$.

Columns 9 and 10 display the integrated flux density (S_{int}) and its uncertainty ($\sigma_{S_{int}}$), respectively, in mJy. The uncertainty $\sigma_{S_{int}}$ is defined as the quadrature sum of the absolute calibration error and the local rms noise.

Column 11 contains the SNR of each source. Multiple component sources have SNR=-99.

Column 12 is the resolved flag. If a source is resolved, this value is 1, and if it is unresolved, this value is 0. All multiple-component sources are resolved.

Column 13 is the multiple component flag. If a source has multiple components (or a component is part of a multiple-component source), this value is 1. Otherwise, this value is 0.

Columns 14 and 15 display the deconvolved source size θ and its associated uncertainty σ_θ, both in arcseconds. Unresolved sources have their deconvolved sizes set to 0 arcsec.

A detailed description and a full version of the radio catalogue is available in Butler et al 2017 [6].

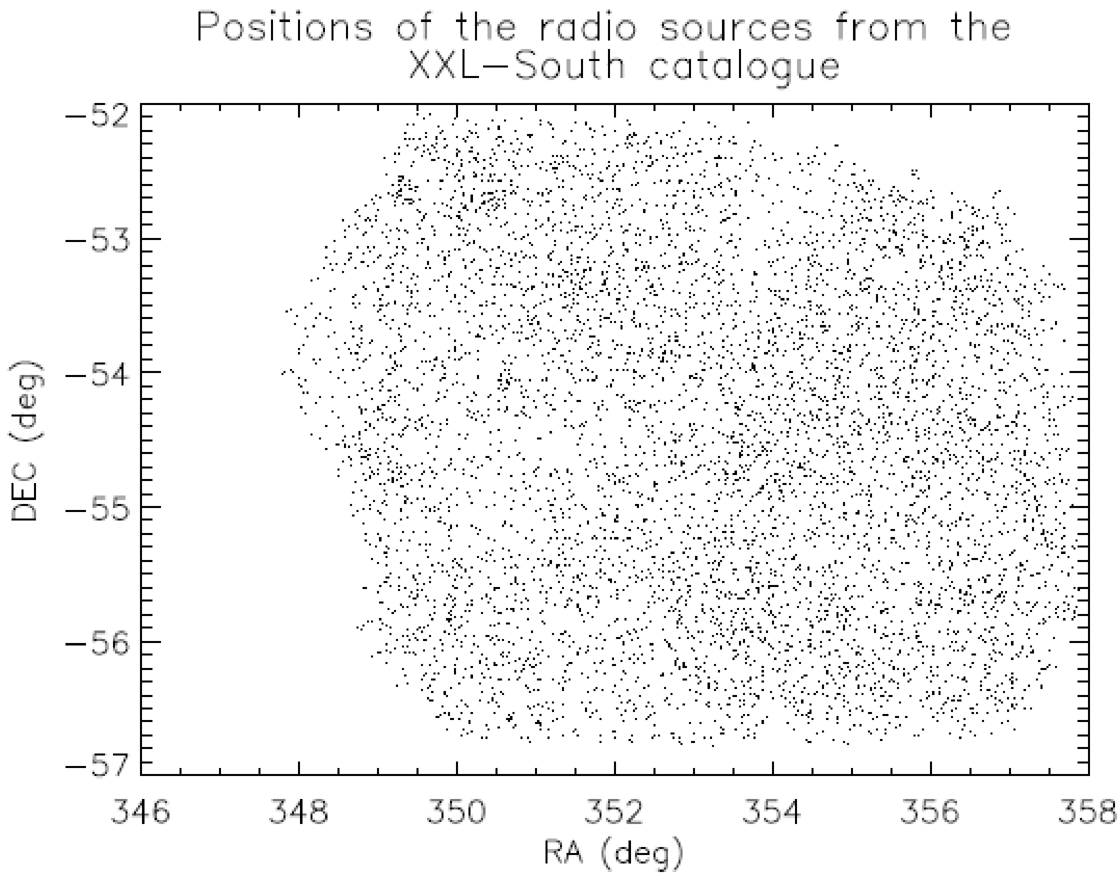

Figure 2.1: Positions of the sources from the XXL-South radio catalogue

2.2 Optical and Near infrared data

Optical data that I used in this work was obtained by several telescopes.

Three public European Southern Observatory (ESO) large programme surveys have observed the XXL field in the near infrared with the Visible and Infrared Survey Telescope for Astronomy[1] (VISTA) in various depths.

In particular, XXL-South, that is our field of interest, was covered by one of those three public European Southern Observatory (ESO) large programme surveys, the VISTA Hemisphere Survey (VHS, PI: R., McMahon), in the J, H and K near infrared filters.

The Blanco Cosmology Survey [2] (BCS; Desai et al. 2012 [10]) has targeted an area of $80\ deg^2$ which overlaps with the XXL-S field using the MOSAIC II imager at the *Cerro Tololo Inter-American Observatory*[3] (CTIO). The observations cover the *g, r, i, z* bands (4850 - 9000 Å). The images used in this work were analysed as described in Menanteau et al. (2009) [44].

The *Dark Energy Camera*[4] (DECam) is the successor of the MOSAIC II camera at CTIO. The XXL collaboration observed the XXL-S field (PI: C. Lidman) in the *g, r, i, z* bands (4850 - 9000 Å), but at deeper depth compared to BCS. The details of the observations and data reduction are in Gardiner et al. (in preparation). The stacked images used in this work were performed as described in Desai et al. (2012) [10].

Detailed description of the optical catalogue used in this work can be find in paper by S. Fotopoulou et al, 2016. [11]

This catalogue consists out of 4 143 094 sources and 15 different magnitudes from the ultraviolet to the near infrared.

An overlap of the radio and optical positions in all the bands is reported in Figure 2.2 and 2.3.

---

[1] http://www.eso.org/public/teles-instr/surveytelescopes/vista/
[2] http://www.usm.uni-muenchen.de/BCS/
[3] http://www.ctio.noao.edu/noao/
[4] http://www.ctio.noao.edu/noao/content/dark-energy-camera-decam

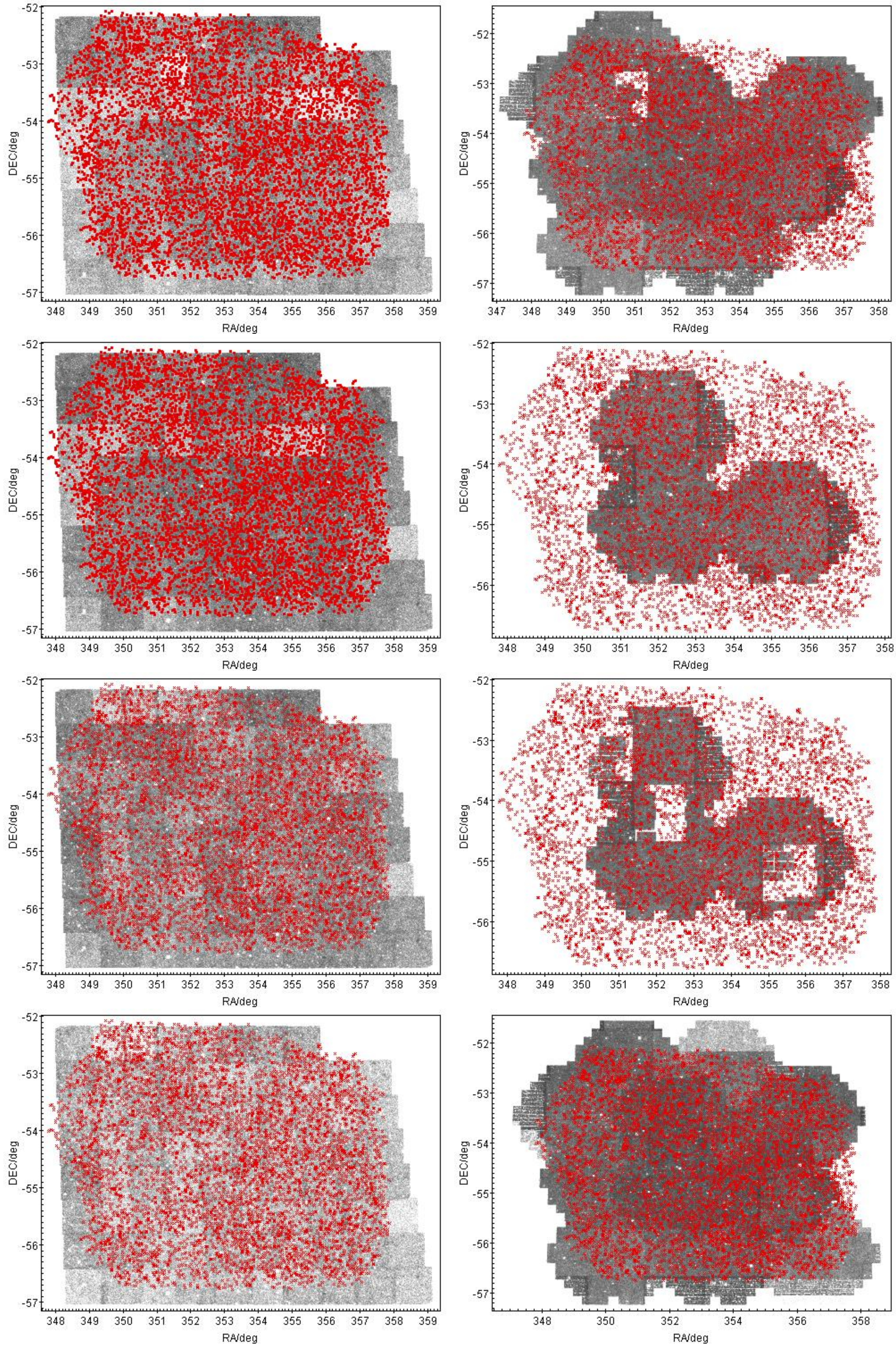

Figure 2.2: Overlap between positions of the optical sources, noted in black and positions of radio sources, noted in red. From top left to bottom right, the bands are: g_{BCS}, g_{DEC}, r_{BCS}, r_{DEC}, i_{BCS}, i_{DEC}, z_{BCS} and z_{DEC}

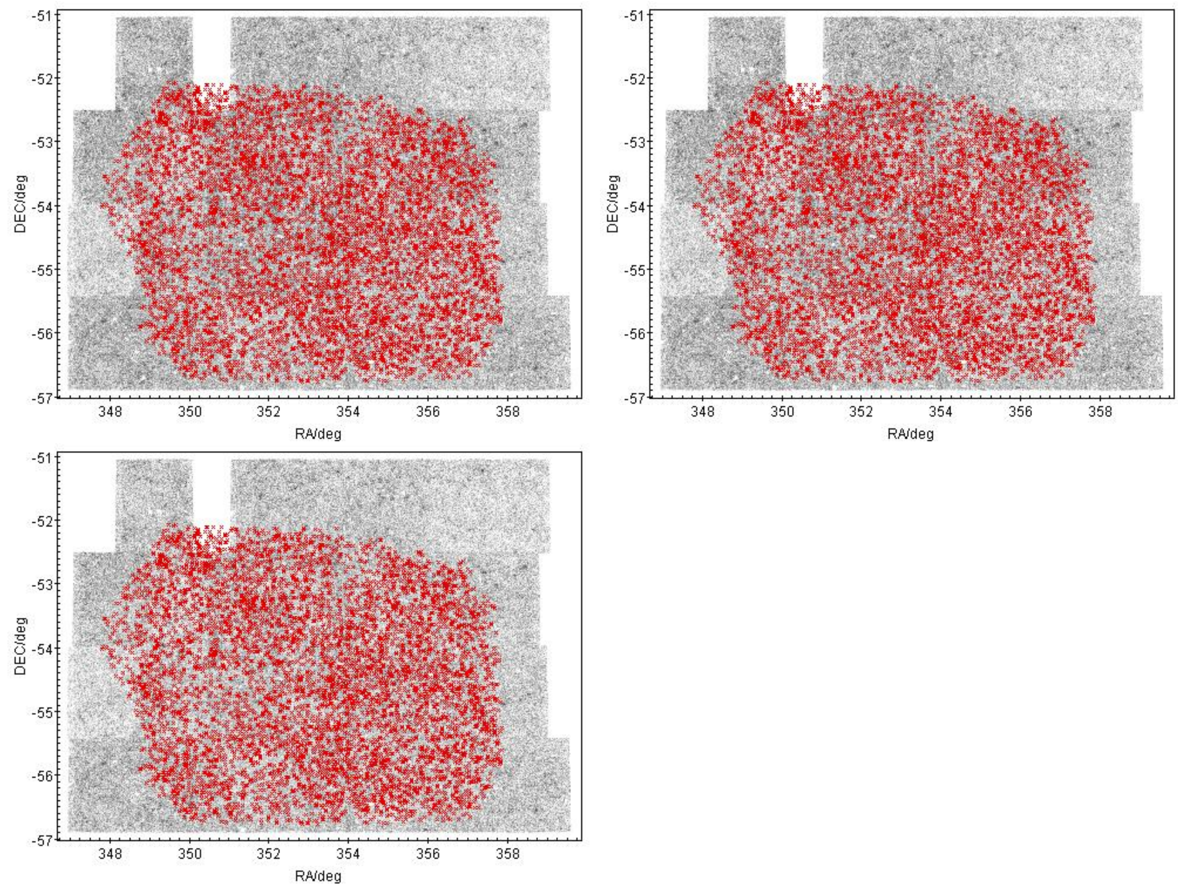

Figure 2.3: Overlap between positions of the NIR sources, noted in black and positions of radio sources, noted in red. From top left to bottom, the bands are: J, H and K

3 Technique used

For the optical identification of these 6293 radio sources, I used the likelihood ratio (LR) technique [5, 7, 38].

The likelihood ratio is defined as the ratio between the probability that a given source is the true optical counterpart, and the probability that the same source is an unrelated background object:

$$LR = \frac{q(m)f(r)}{n(m)}, \tag{3.1}$$

where $q(m)$ is the expected probability distribution of the true optical counterparts as a function of magnitude, $f(r)$ is the probability distribution function of the positional errors and $n(m)$ is the surface density of background objects with magnitude m (see Ciliegi et al. 2003 [7] for a detailed discussion on the procedure to calculate $q(m)$, $f(r)$ and $n(m)$).

For each source I adopted an elliptical Gaussian distribution for the positional errors with the errors in RA and DEC on the radio position reported in the radio catalogue and assuming optical position uncertainty as a value of 0.3 arcsec.

I adopted a 3 arcsec radius for the estimate of $q(m)$, obtained by subtracting the expected number of background objects ($n(m)$) from the observed total number of objects listed in the catalogue around the positions of the radio sources.

With this procedure, $q(m)$ is well defined up to the magnitudes of approximately $23.0 - 23.5$, depending on the band. At fainter magnitudes, the number of objects around the radio sources turned out to be smaller than that expected from the field global counts $n(m)$. That would result in an unphysical negative $q(m)$, which would not allow the application of this procedure at these magnitudes. This effect can be clearly seen in the magnitude distributions of Figure 3.1, where for the z_{DEC} band catalogue I report the background magnitude distribution $n(m)$ (dashed histogram), the observed magnitude distribution around each radio sources within a radius of 3 arcsec (solid histogram) and the expected magnitude distribution of the true optical counterparts $q(m)$ (dashed-dot-dot-dot histogram) calculated as difference of the two previous distributions. At magnitudes fainter than z=23.5 we have the unphysical situation that the observed magnitude distribution around the radio sources is lower than the value of the background distribution. This effect was already noted by Brusa

et al. 2006 [5] during the identification of the X-ray sources in the COSMOS field.
The reason for this effect is the presence of a large number of relatively bright optical counterparts close to the radio sources. These objects make it difficult to detect fainter background objects in the same area. As a consequence, the background distribution estimated from the global field is an overestimate at faint magnitude of the background distribution estimated around the radio sources. This situation is visually represented in Figure 3.2, where a bright optical galaxy has been assumed as optical counterpart of a radio sources, the position of which is represented by the red cross. The red big circle represents the area used to estimate the observed magnitude distribution around the radio sources (a circle of radius 3 arcsec in our case). In this example there are 8 sources that should contribute to the observed magnitude distribution: the bright optical galaxy (counterpart of the radio sources) + seven background sources represented by the seven stars in the figure (five yellow six-pointed stars plus two blue five-pointed stars). However, while the bright galaxy and the five six-pointed sources are easily detected and will contribute to the observed magnitude distribution, the two five-pointed objects cannot be detected because they are in the area masked by the bright galaxy, generating an underestimation of the magnitude distribution.
In order to estimate the correct $n(m)$ to be used at faint magnitudes in the likelihood calculation I used the technique described bellow. I have randomly extracted 5000 sources from the optical sample with the same magnitude distribution expected for the optical counterparts. Then I computed the background surface density around these objects. The $n(m)$ computed with this method is consistent with the global $n(m)$ for brighter magnitudes (approximately up to $23.0 - 23.5$), but is significantly smaller than it at fainter magnitudes. Therefore, for brighter magnitudes, as the input $n(m)$ in the likelihood procedure, I used the global one, while for the fainter magnitudes, I used the $n(m)$ computed in the aforementioned way. This allowed me to identify a few tens of very faint sources that would have been missed without this correction in the expected $n(m)$. In Figure 3.3 the new $n(m)$ and $q(m)$ distributions calculated with the new method explained above are shown. As shown in the figure, now the observed (solid line) magnitude distribution around the radio sources (background + counterparts of radio sources) is, as expected, always greater than the background distribution (dashed line), giving a $q(m)$ distribution without negative values. The

presence or absence of more than one optical candidates for the same radio source gives us additional information to that contained in LR. The reliability Rel_j for object j being the correct identification is given by the equation [38]:

$$Rel_j = \frac{LR_j}{\sum_i (LR)_i + (1 - Q)}, \tag{3.2}$$

where the sum is over the set of all candidates for this particular source, while Q is the probability that the optical counterpart of the source is brighter than the magnitude limit of the optical catalogue ($Q = \int^{m_{lim}} q(m)dm$). The adopted value for Q is 0.8 [7]. Once $q(m)$, $f(r)$ and $n(m)$ were obtained, I computed the LR value for all the optical sources within a distance of 3 arcsec from the radio position. Having determined the LR for all the optical candidates, I had to choose the best threshold value for LR (L_{th}) to discriminate between spurious and real identifications. As LR threshold I adopted $L_{th} = 0.2$. With this value, according to Eq. (3.2) and considering that our estimate for Q is 0.8, all the optical counterparts of radio sources with only one identification (the majority in our sample) and $LR > LR_{th}$ have a reliability greater than 0.5.

I applied this technique on 7 optical (g, r, i, z) and near infrared (J, H, K) bands, which resulted in 7 catalogues. I combined those 7 catalogues into final cross radio - optical match catalogue.

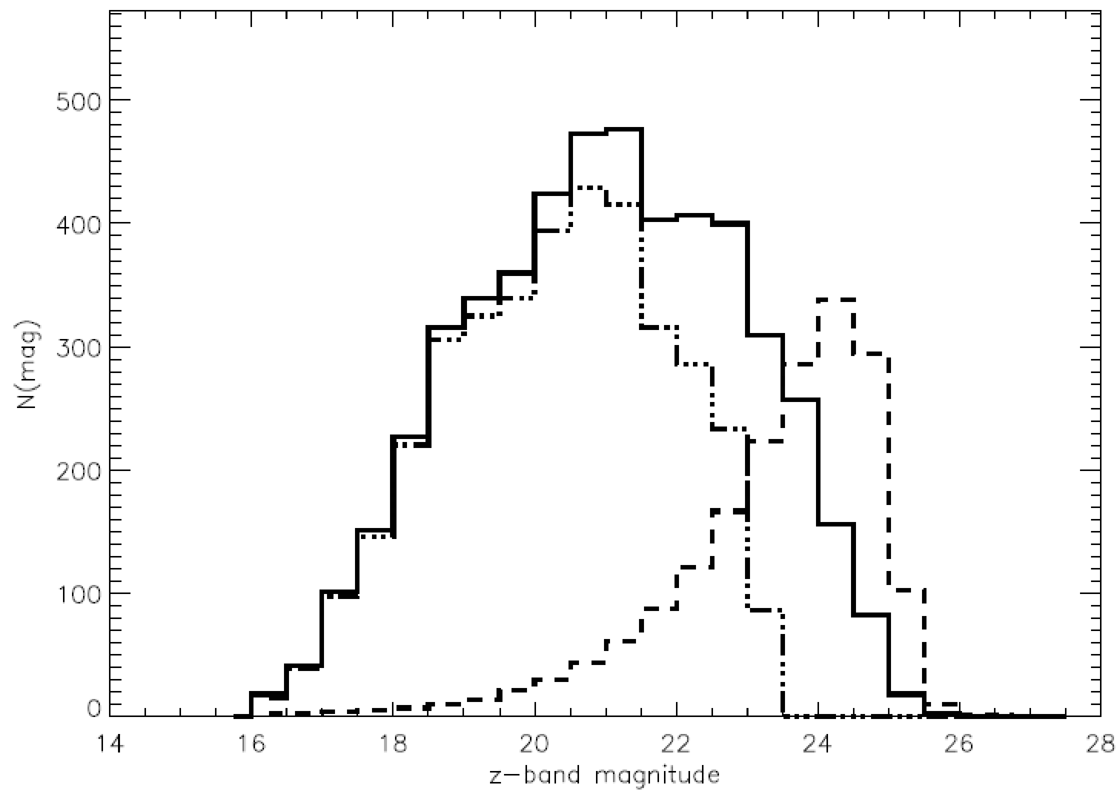

Figure 3.1: The observed magnitude distribution of all optical objects present in the z_{DEC} band catalogue within a radius of 3 arcsec around each radio source is shown as solid histogram. The expected distribution of background objects in the same area $n(m)$ is shown as dashed histogram. The difference between these two distributions ($q(m)$) is shown with a dashed dot dot dot histogram. At magnitude fainter than z=23.5 the $q(m)$ histogram has unphysical values

Figure 3.2: Visual representation of the effect that produce a negative value at faint magnitude of the expected probability distribution of the true optical counterpart. Due to the presence of a large number of relatively bright optical counterparts (as represented in figure), faint background objects in the area masked by the bright sources (represented by five-pointed stars in the figure) are not detected, generating an underestimation of the observed magnitude distribution calculated around the position of the radio sources.

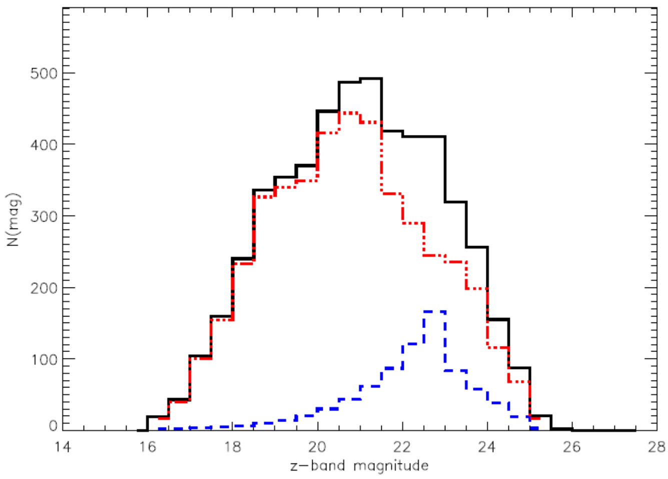

Figure 3.3: The observed magnitude distribution of all optical objects present in the z_{DEC} band catalogue within a radius of 3 arcsec around each radio source, $q(m)$, is shown as solid histogram. The expected distribution of background objects in the same area, estimated using the procedure described above, $n(m)$ is shown as dashed histogram. The difference between these two distributions is shown with dashed – dotted histogram

4 Results obtained

During the work done for this Thesis, I applied LR technique on all of our 7 different optical and NIR bands and accepted as reliable counterparts all the optical/NIR sources for which $LR > LR_{th}$, where $LR_{th} = (1 - Q) = (1 - 0.8) = 0.2$.
When for a given radio sources there were two optical counterparts with $LR > LR_{th}$ I retained only the optical/NIR sources with the highest reliability, where the reliability is defined as in eq. (3.2).
I merged the 7 optical and NIR catalogues in one master catalogue. When for a radio source, in the master catalogue, two (or more) different counterparts (i.e. different optical/NIR sources) were available (i.e. from LR catalogue from different bands), I tried to find a band where the possible counterparts are both proposed as optical/NIR counterparts. In this case, I decided the counterpart on the basis of the reliability from that band.
Finally, in the case I didn't see both the possible optical/NIR counterparts in a single band, I decided using the general reliability (i.e. the reliability associated to each optical/NIR counterpart calculated in different optical/NIR band).

Short summary of the results is shown in Table 4.1. It consists of the number of

Bands	g_{BCS}	g_{DEC}	r_{BCS}	r_{DEC}	i_{BCS}	i_{DEC}	z_{BCS}	z_{DEC}	J	H	K
Inside CCD area	6110	5386	6115	2676	6103	2357	-99	6023	6101	6107	6111
3 arcsec	3337	4076	4369	2316	4349	2055	-99	5139	3778	3935	4034
reliable id	2888	3379	3720	1885	3814	1719	-99	4412	3539	3702	3813

Table 4.1: This table shows number of sources inside the CCD area, number of optical/NIR objects found around radio sources using a circle of radius 3 arcsec and number of sources with reliable identification for each optical and near infrared band

radio sources inside the CCD area, number of optical/NIR objects found around radio sources using a circle of radius $3''$ and number of sources with reliable identification for each optical and near infrared band.
Out of 6293 radio sources, 6176 are inside the CCD area when looking at all the bands together. I found that all together 4738 radio sources have an optical/NIR counterpart. These 4738 radio sources, as well as their coordinates and fluxes, are now put together in a new master catalogue with their optical/NIR counterparts, magnitudes and distances between radio and optical/NIR position.
Figures 4.1, 4.2 and 4.3 show the LR output for optical and NIR bands, where black

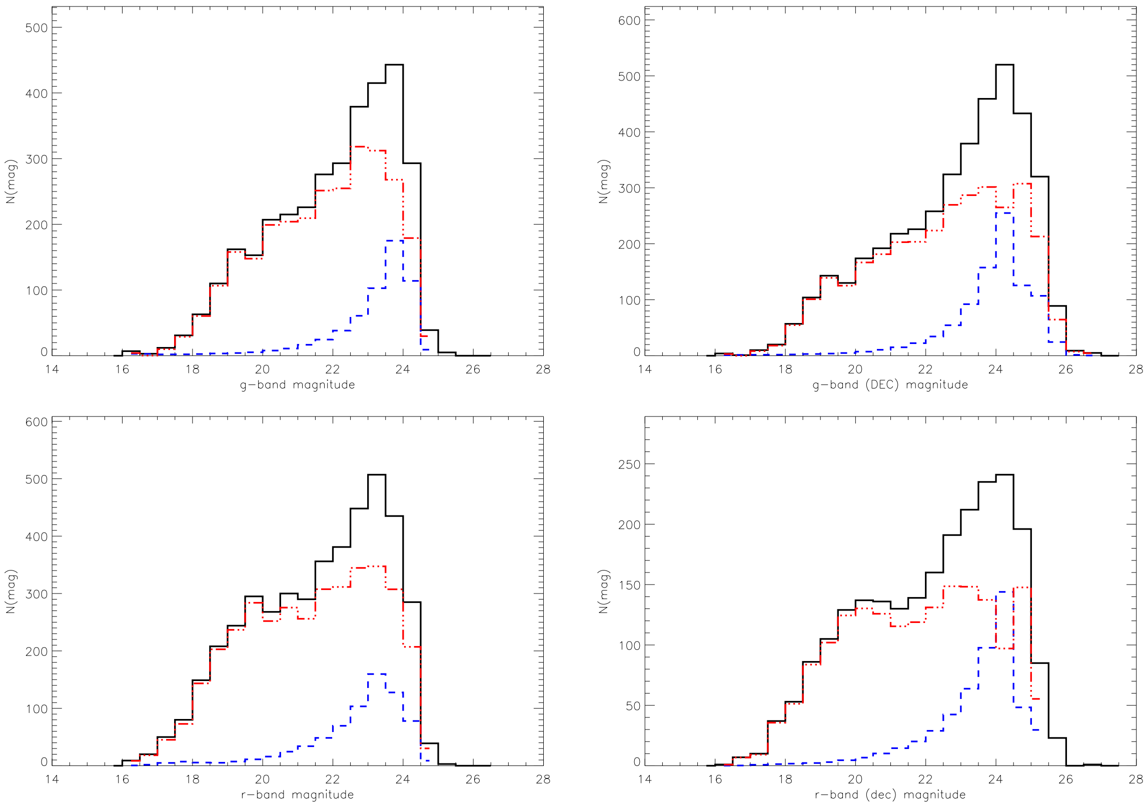

Figure 4.1: LR output for g_{BCS}, g_{DEC}, r_{BCS} and r_{DEC} bands. The observed magnitude distribution of all optical objects present in the relative band catalogue within a radius of 3 arcsec around each radio source, $q(m)$, is shown as solid histogram. The expected distribution of background objects in the same area, $n(m)$ is shown as dashed histogram. The difference between these two distributions is shown with dashed – dotted histogram.

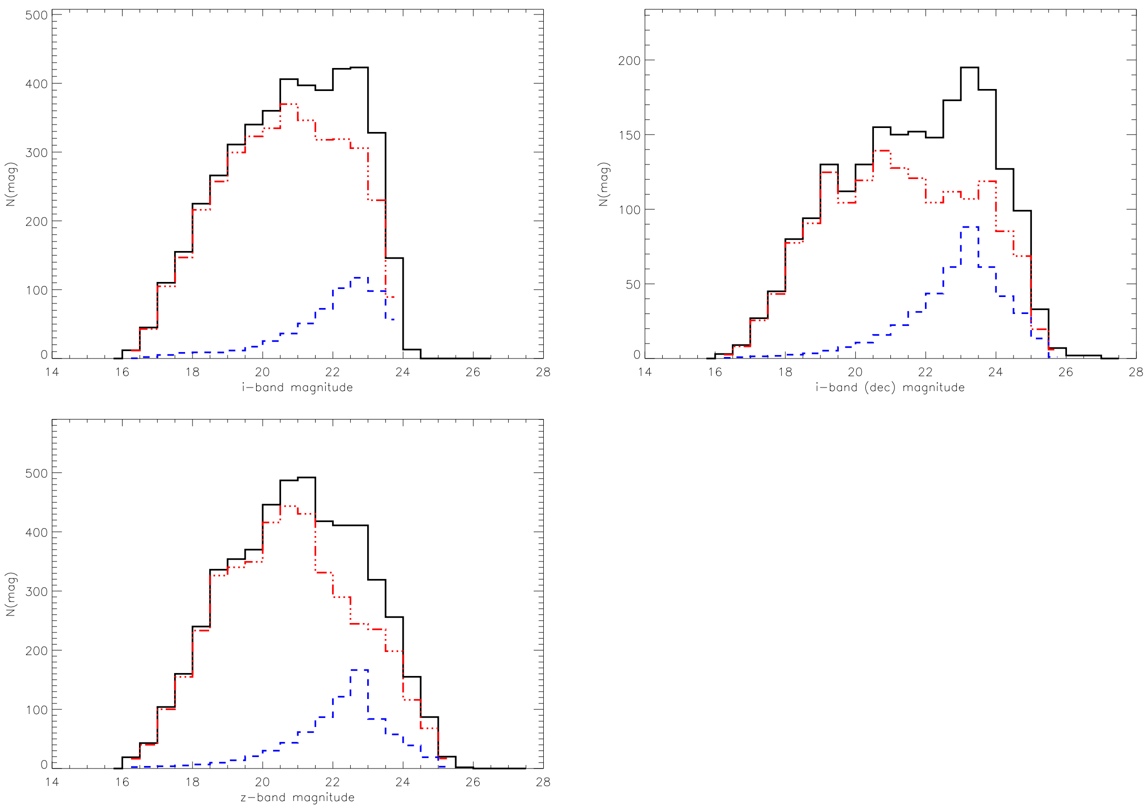

Figure 4.2: LR output for i_{BCS}, i_{DEC} and z_{DEC} bands. The observed magnitude distribution of all optical objects present in the relative band catalogue within a radius of 3 arcsec around each radio source is shown as solid histogram. The expected distribution of background objects in the same area is shown as dashed histogram. The difference between these two distributions is shown with dashed – dotted histogram.

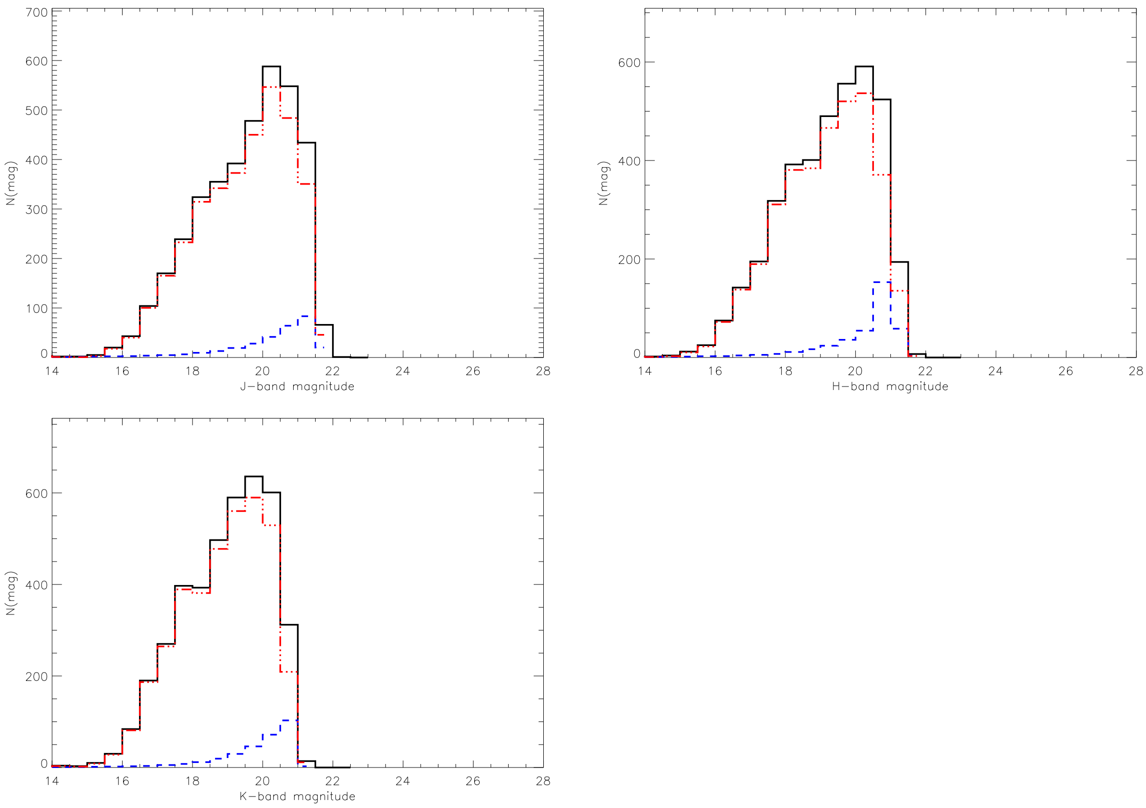

Figure 4.3: LR output for J, H and K bands. The observed magnitude distribution of all objects present in the relative band catalogue within a radius of 3 arcsec around each radio source is shown as solid histogram. The expected distribution of background objects in the same area is shown as dashed histogram. The difference between these two distributions is shown with dashed – dotted histogram.

solid line represents observed magnitude distribution of all optical/NIR objects present in the shown band optical catalogue, within a radius of 3″ around each radio source. Blue dashed line is the expected distribution of background objects in the same area. The difference between these two distributions (black and blue) is the expected magnitude distribution of the optical/NIR counterparts, shown in red.

5 Optical properties of the radio galaxies

5.1 Spectroscopic redshift

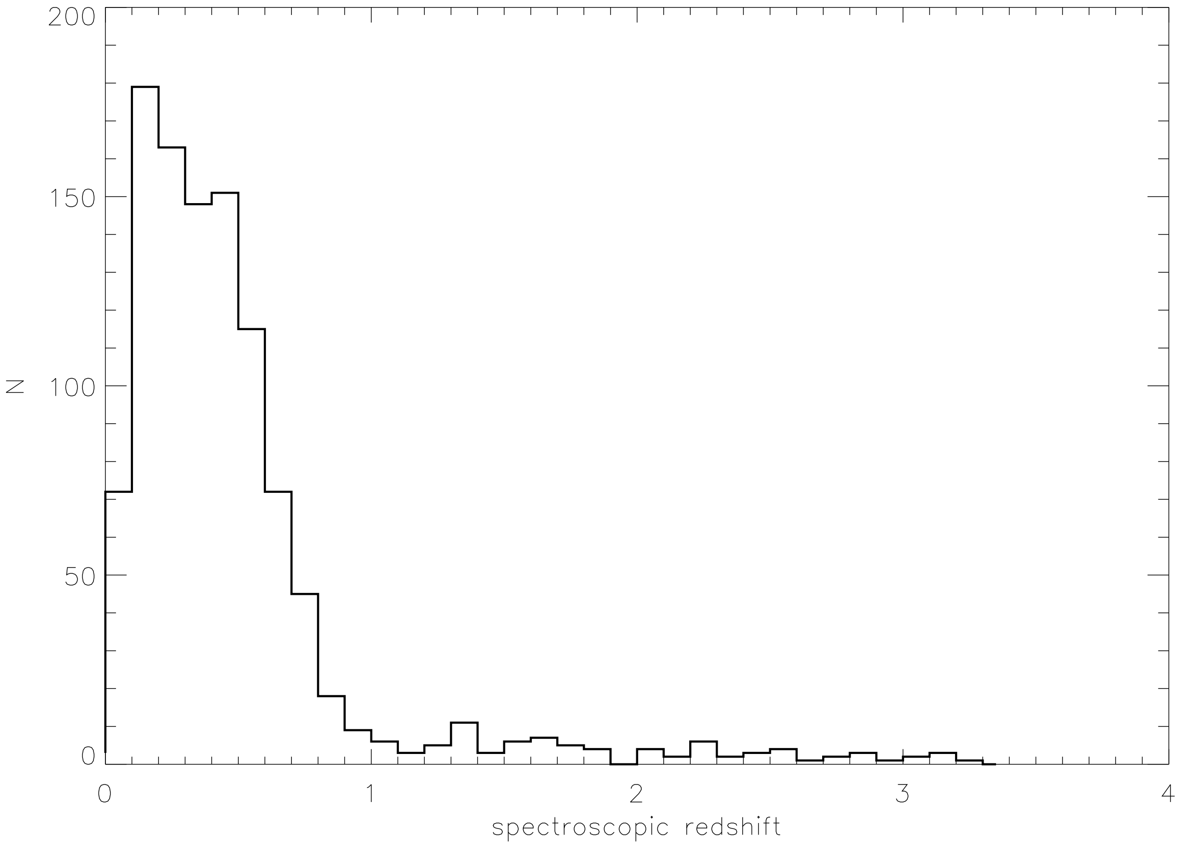

Figure 5.1: Spectroscopic redshift distribution available for 1056 out of 4738 optical/NIR counterparts of radio galaxies

Dr Sotiria Fotopoulou, from the Department of Astronomy at the University of Geneva in Switzerland, provided us with spectroscopic redshift for 1056 out of 4738 radio galaxies with reliable optical/NIR identification. Spectroscopic redshift distribution of radio sources with reliable optical/NIR identification can be seen in Figure 5.1. About 90% of the sources are estimated to be at $z \leq 1$ with a small high redshift tail extending up to $z \approx 3$.

Number of radio sources with reliable optical/NIR identification in each redshift bin

Redshift bins	0≤z<0.5	0.5≤z<1	1≤z<1.5	1.5≤z<2	2≤z<2.5	2.5≤z<3	3≤z<3.5
N of identification	713	259	28	22	17	11	6

Table 5.1: This table shows number of radio sources with reliable optical/NIR identification in each redshift bin

is shown in Table 5.1.

Left plot in Figure 5.2 shows total radio flux distribution for the whole radio sample

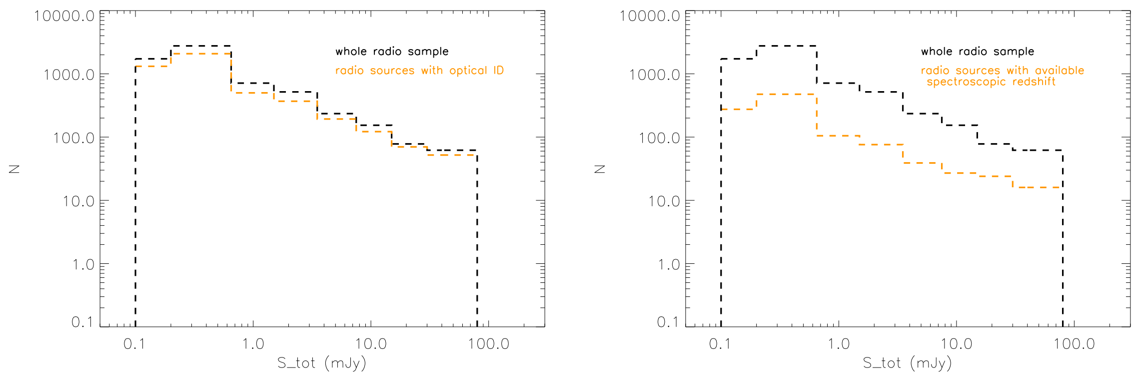

Figure 5.2: Total radio flux distribution for the whole radio sample (black histogram) and for the 4738 radio sources with a reliable optical/NIR identification (orange histogram) is shown on the left plot while the right plot shows total radio flux distribution for the whole radio sample (black histogram) and for the 1056 radio sources for which a spectroscopic redshift is available (orange histogram)

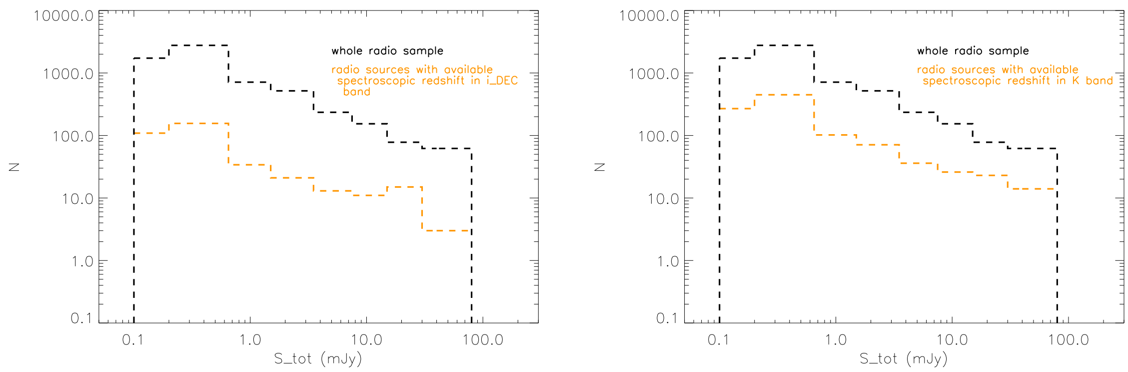

Figure 5.3: Total radio flux distribution for the whole radio sample (black histogram) and for the 366 radio sources for which a spectroscopic redshift and i_{DEC} magnitude is available (orange histogram) is shown on the left plot while the right plot shows total radio flux distribution for the whole radio sample (black histogram) and for the 1007 radio sources for which a spectroscopic redshift and K−band magnitude is available (orange histogram)

(black histogram) and for the 4738 radio sources with a reliable optical identification (orange histogram). Since that plot is logarithmic, we can see that the difference is actually much bigger at low flux than at high fluxes. This indicates that the majority of the radio unindetified sources are faint sources.

On the right plot in Figure 5.2 we can see total radio flux distribution for the whole radio sample (black histogram) and for the 1056 radio sources for which a spectroscopic redshift is available (orange histogram). From this plot we can see that those 1056 radio sources with available spectroscopic redshift are representative of the whole sample.

The same explanation goes to Figure 5.3 where on the left plot we can see radio flux distribution for sources with spectroscopic redshift and i_{DEC} magnitude (orange histogram). Right plot shows radio flux distribution for sources with spectroscopic redshift and K−band magnitude (orange histogram). Black histogram, as in previous plots, denotes total radio flux distribution for the whole radio sample.

5.2 Magnitude distribution and colour diagrams

Study of the magnitude and colour distributions of the optical/NIR counterparts of the radio galaxies can give us some clues on the nature of faint radio sources.

The magnitude distribution of the optical/NIR counterparts of the radio sources is

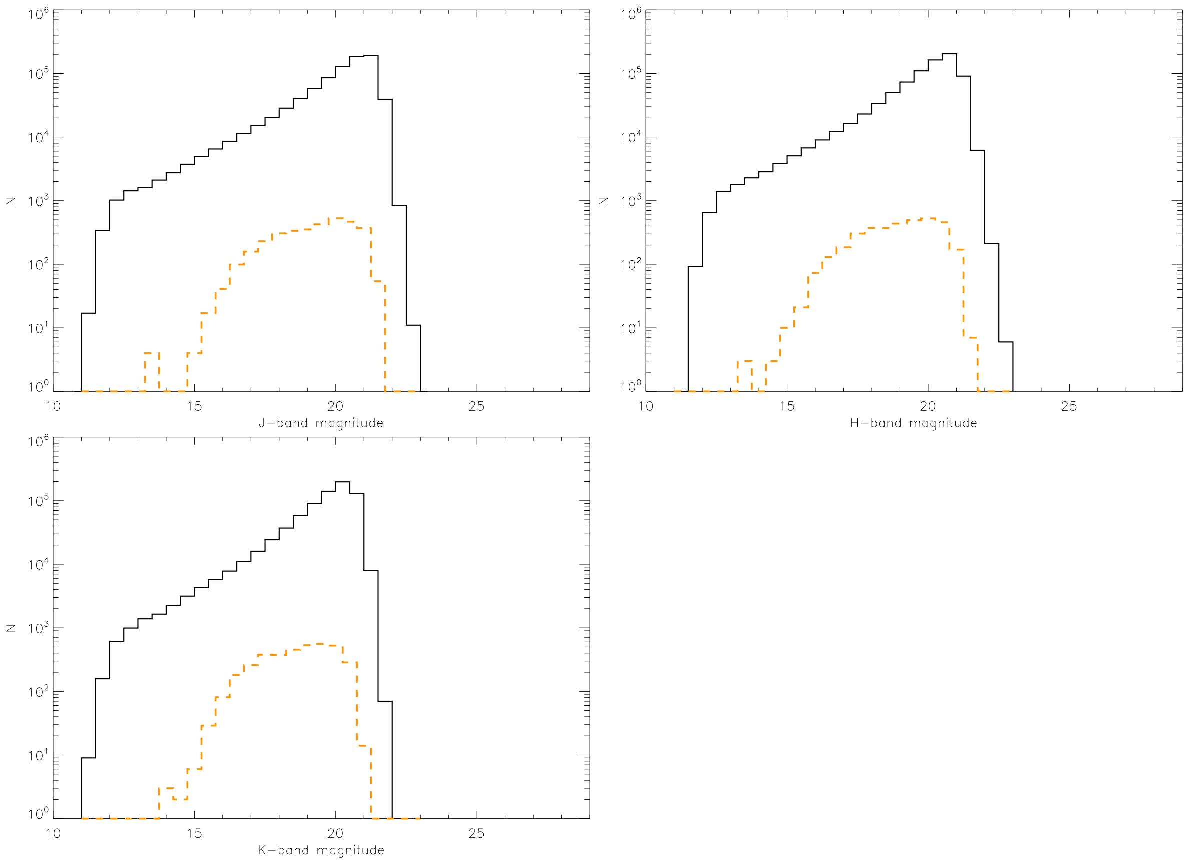

Figure 5.4: Magnitude distribution of the whole optical sample (black empty histogram) and the magnitude distribution of the radio sources with reliable NIR identification (orange empty histogram). From top left to bottom: J, H, K

shown as orange histogram in Figure 5.4 and 5.5, while the black histogram shows the magnitude distribution of the whole optical/NIR data set in the observed band. We can see that the magnitude distribution of the optical/NIR counterparts of the

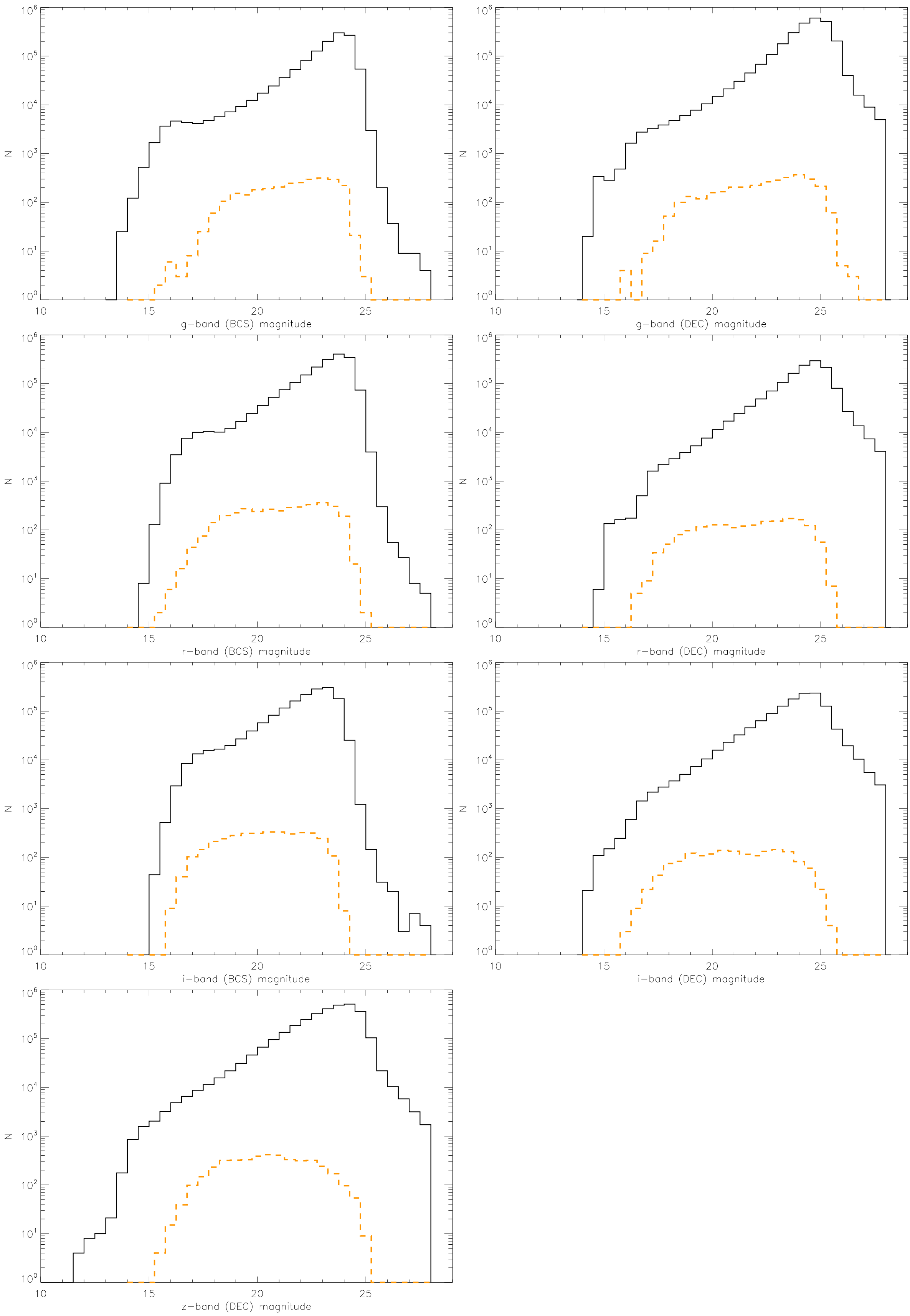

Figure 5.5: Magnitude distribution of the whole optical sample (black) and the magnitude distribution of the radio sources with reliable optical identification (orange). From top left to bottom right: g_{BCS}, g_{DEC}, r_{BCS}, r_{DEC}, i_{BCS}, i_{DEC}, z_{BCS} and z_{DEC}

radio sources is flatter than the one from the global optical catalogue, showing that a significant fraction of radio sources is associated with relatively bright optical galaxies/AGN. Moreover, it is interesting to note that magnitude distributions of the radio sources have a peak coincident with the peak of the total distribution, i.e. coincident with the magnitude limit of the optical and NIR data. This result shows that the relative low fraction of optical/NIR identification of radio sources (4738/6176 $\approx$ 77% of the radio sources within CCD area) is mainly due to a non very deep limiting magnitude of the optical/NIR data. With a deep optical/NIR data we could expect a higher fraction of identification and an optical magnitude distribution of the radio sources with a maximum brighter than the limiting magnitude.

In astronomy, a colour is defined as the difference between a magnitude at one wavelength and a magnitude at another wavelength. On a colour-colour diagram, we plot one colour versus another colour. Another useful plot is a colour-magnitude diagram, which plots the magnitude at a certain wavelength versus some colour.

In Figure 5.6 the I-K colour is shown as a function of the total radio flux, of the I band magnitude and of the radio-to-optical ratio, *R*, for various redshift bins. Radio-to-optical ratio *R* is defined as

$$R = S \times 10^{0.4(I-12.5)}, \tag{5.1}$$

where S is the radio flux in mJy and I is the apparent magnitude of sources. While no obvious correlation is seen between I-K and radio flux, there appear to be significant correlations between I-K and both I band magnitude and radio-to-optical ratio, R. A similar trend for for optically fainter radio sources to have redder I-K colours was already noted by Richards et al. 1999 [29] and Ciliegi et al. 2003 [7]. Moreover, from plots in Figure 5.6 it is also evident a correlation with the redshift. Moving from the redshift bin 0-0.5 (blue points in Figure 5.6) to z=0.5-1.0 (orange points) the radio sources become more red and with and higher radio-to-optical ratio. This trend could suggest that the sources without spectroscopic redshift (light gray in Figure 5.6) could be high redshift sources, some of which can be classified as Extremely Red Galaxies (EROs), i.e. sources with I-K $>$ 4 (see top right plot in Figure 5.6).

Various authors used colour-colour diagrams and the overall spectral energy distribution to attempt to discriminate between passively evolving elliptical or dusty

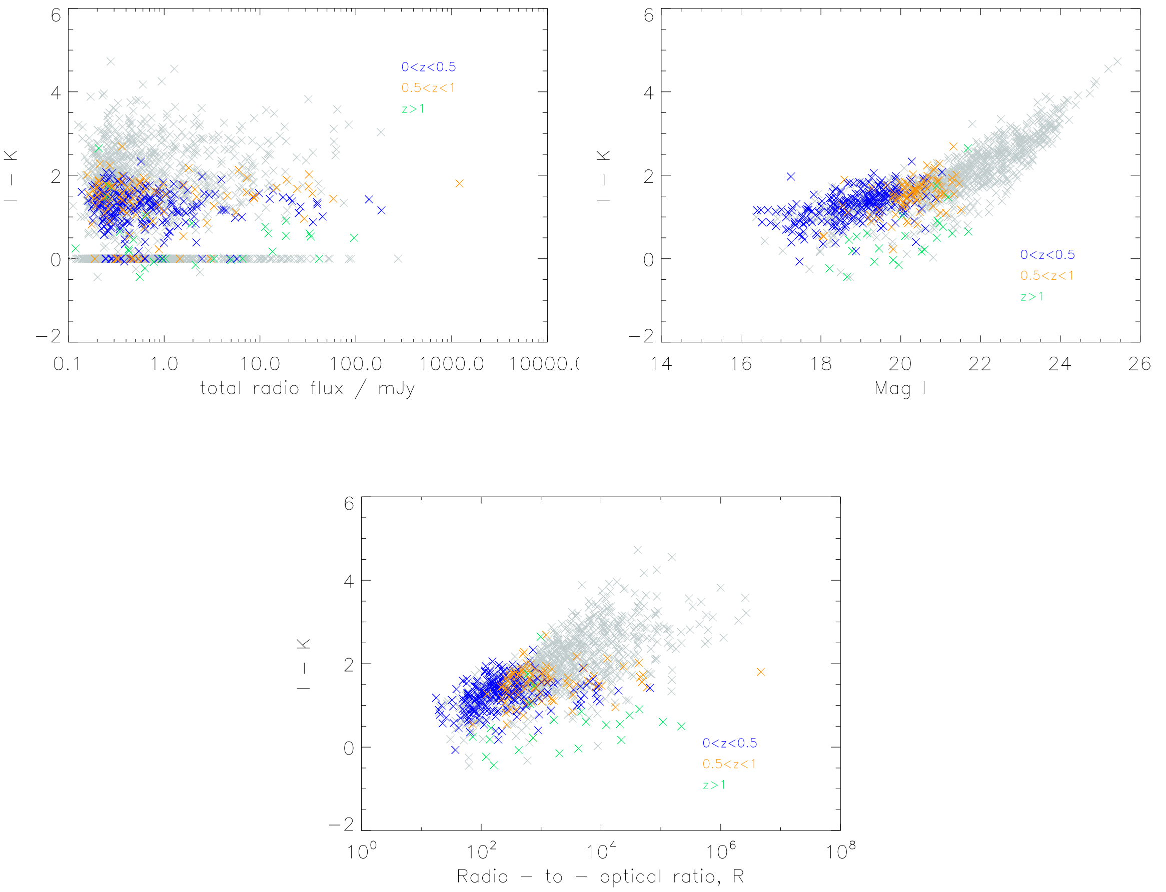

Figure 5.6: The I–K colour as a function of the total radio flux (left top panel), of the I band magnitude (right top panel) and of the radio-to-optical ratio R (bottom panel). Different color denotes different redshift bin, while in the background, in light gray, are shown the sources without spectroscopic redshift

star–forming galaxies [27, 41].

Previous studies on the optical identifications of radio sources [7, 13, 14, 19, 28, 29] have suggested that the majority of the sources with low radio-to-optical ratio, R, are associated with star forming galaxies, which are characterized by moderately weak intrinsic radio power. At the same time, sources with higher R are linked to early type galaxies in which radio luminosity is likely connected to nuclear activity. They cover a much larger range in radio power, which makes them the dominant population at high R. On the basis of the results shown in Figure 5.6 we could suggest that the radio sources associated at star forming galaxies (bluer colours and low radio-to-optical ratio, R) are probably low redshift galaxies, while radio sources associated at early type galaxies (redder color and higher R) are objects at higher redshift.

6 Summary and conclusions

In this Master's Thesis I presented the optical identifications of the 6293 radio sources detected in the 2.1 GHz deep radio survey down to a median rms of $\sigma \approx 41\mu$Jy/beam obtained with Australia Telescope Compact Array (ATCA) in the XMM-Newton Extragalactic Legacy Survey South (XXL-S) field.
For the optical identification of these 6293 radio sources, I used the likelihood ratio (LR) technique [5, 7, 38] that I applied on 4 optical (g, r, i, z) and 3 NIR bands (J, H and K).
Applying this technique resulted in 7 catalogues that I combined into final cross radio - optical match catalogue. In the final catalogue we have combined optical and radio properties such as: positions, fluxes, magnitudes and redshift. This catalogue is a fundamental tool to study the multi-wavelength properties of the radio sources in the XXL-S filed. In this thesis I analyzed only the optical and near infrared properties of the radio sources. However, the catalogue produced during this thesis can be used as the "first stone" to further extend the analysis of the SED of the radio sources, including, in a second step, all the other available data (e.g. the X-ray data).
Short summary of the results is shown in Table 4.1. It consists of the number of radio sources inside the CCD area, number of optical objects found around radio sources using a circle of radius 3″ and number of sources with reliable identification for each optical and near infrared band.
Out of 6293 radio sources, 6176 are inside the CCD area when looking at all the bands together. We found that all together 4738 radio sources have an optical counterpart, giving a fraction of identification around 77% (4738/6176). This fraction of identification is relatively low in comparison to similar work conducted in other radio fields. Recently, for example, Smolčić et al 2017 [37] have found counterparts for 93% of the radio sources in the COSMOS field. From the analysis done during this thesis, we find that the relative low fraction of optical/NIR identifications of radio sources is mainly due to a non very deep limiting magnitude of the optical/NIR data. Moreover, we find that a significant fraction of radio sources is associated to relatively bright galaxies while the majority of the radio sources without an optical/NIR counterpart are faint radio sources.
Spectroscopic redshift are available for 1056 out of 4738 radio galaxies with reliable

optical identification. About 90% of the sources are estimated to be at $z \leq 1$ with a small high redshift tail extending up to $z \approx 3$. From the analysis of the optical colour properties, we find that the sources for which we didn't have spectroscopic redshift could be high redshift sources, some of which can be classified as Extremely Red Galaxies (EROs). Finally, combining the colour properties and the spectroscopic information, we concluded that the radio sources associated with star forming galaxies (bluer colours and low radio-to-optical ratio, *R*) are probably low redshift galaxies, while radio sources associated with early type galaxies (redder colour and higher R) are objects at higher redshift.

7 The methodical part of the Master's Thesis

7.1 Introduction

Astronomy is one of the oldest sciences known. People have always asked themselves about celestial bodies and phenomena that surrounds them. Throughout the centuries, they have looked to the stars to help them navigate across open oceans or featureless deserts, know when to plant and harvest, and to preserve their myths and folklore. Ancient people used the appearance or disappearance of certain stars over the course of each year to mark the changing seasons.
With religious, political and technological difficulties, cosmological theories have changed from geocentric to heliocentric, up to the modern astronomy and the Big Bang Theory. In spite of astronomy's long presence in human life, research in the field of astronomy education is just beginning.

7.1.1 Content related to astronomy in Croatian schools

In Croatia, there is non compulsory astronomy class in only a few secondary schools. Fundamental knowledge of basic concepts of astrophysics, like the Solar System, the astronomical phenomena and the Universe, students gain through subjects such as chemistry, geography, biology, mathematics, and physics.
Each individual should be properly and thoroughly educated about the Universe, the Solar System, and the astronomical phenomena that affect our life on Earth. The problem of lack of classes related to astronomy and the amount of misconceptions that occur during the high school years, are not just the problem in Croatia, but also in other countries. Outside of Croatia students also lack in understanding of the basic terms and concepts that, many would agree, fall into basic general knowledge.
In Croatia, the expected achievements from all subjects in elementary school and high school are determined by the National Curriculum [12].
In National Curriculum, in the *Evolution of the Universe* section, there is a list of achievements related to astronomy.
In vocational high schools, students will be able to:

- describe, on the basis of the observation, the main objects in the Universe: stars, constellations, galaxies, and clusters of the galaxies

- explain the Big Bang Theory as the beginning of "Space-Time" and the expansion and cooling of the Universe After the Big Bang
- discuss pervading the Universe by the gravity force
- describe the evolution of the Sun and its radiation
- describe the Earth's age in relation to the Universe and to establish the time period of the existence of Homo sapiens on Earth
- explain the thermonuclear processes in the stars and the radiation of the energy
- describe the relationship between dark and visible matter in the Universe

In grammar schools, besides the aforementioned achievements, students will also be able to show and explain simple models and simulations of planetary and star systems.
In the first grade of high school topics that handle the concepts from areas of astronomy are:

- Straight motion
  - basic ideas from astronomy as the Earth's rotation around its axis, time needed for one turn etc.
- The general law of gravity
  - key to understanding Solar System dynamics
  - within this teaching unit, additional topics such as the development from geocentric to heliocentric model or the historical description of Newton's discovery of the general theory of gravitation are offered
  - the phenomenon of high and low tide on Earth is a topic of expanded content

In the second and third grade we deal with astronomy through:

- special theory of relativity
- Doppler effect

In the fourth grade of high school, we complete the course with *Elemental Particles and Universe*. Through this unit most of the content related to astronomy in the high school is being studied. Within this teaching unit, students learn about:

- the distances between the basic celestial bodies
- the diameters of the celestial bodies
- the age of the Universe, the Sun and the Earth
- Big Bang Theory
- Hubble's study of the spectrum of distant galaxies $\rightarrow$ in all distant galaxies spectra, the spectral lines have a red shift $\rightarrow$ all those galaxies are moving away from us
- the link of the galaxy's departure velocity with their distance from Earth $\rightarrow$ Hubble's law
- expansion and cooling of the Universe
- 7 stages of the Universe development (processes, reactions and temperature)
- life cycle of the Sun
- processes within the stars
- radioactive dating

As additional content, in Croatian high schools, neutron stars and black holes are offered.

7.2 Physical concepts, preconceptions and misconceptions

Students form their own concepts under the influence of direct experience, cultural environment and formal education. As such, some ideas related to physical phenomena are also formed before learning physics at school. These are so called preconceptions: spontaneously formed concepts, which do not usually coincide with the physical concepts. They are formed based on experience and simplified reasoning. We can divide the student's alternative conceptions on preconceptions and hybrid

concepts which appear as a combination of preconception and learning.
Misconceptions are generally described as all students' concepts that are not in line with scientific knowledge.
The task of physics teachers is, among other things, to help students to develop more complex scientific reasoning and in the process to help them change their existing ideas that are not compatible with physics. In order to succeed, the existing concept must prove to be unsatisfactory, and this new idea must be understandable, convincing and more fruitful than the old one.
Conceptual change is a cognitive process in which there is emphasis on changing ideas through the learning process. Teacher encourages the conceptual change, but the student is the one who is going through with it. The first step is, of course, the identification of preconceptions/misconceptions, followed by the application of some of the techniques of inducing conceptual changes:

- Cognitive conflict techniques
- Substitution of concepts
- Method of analogy
- Socratic Dialogue

Cognitive conflict and Socratic dialogue represent an intellectual challenge for students, which can be stimulating but also frustrating. On the other hand, the Substitution of the concepts and Method of analogy are milder and easier for students, but for the best results it is still best to combine methods.

7.3 Research

7.3.1 Early reports on astronomy education

One of the earliest summaries in astronomy education was written by Charles Wall in 1973 [1]. He reviewed science education studies in the period 1922-1972.
His report referred to 58 studies in astronomy education, which included students' conceptions of the Moon, day and night cycle, as well as gravity. Contrary to the cognitive focus applied today, Wall recommended that further studies concentrate on the effectiveness of audio-visual materials, laboratory equipment, and individualized

instruction strategies. Wall does not recommend studies that would study deeper student understanding, which is a reflection of the time when school effectiveness was measured in the amount of books in the library instead of investigating student learning and achievement.

The following study was conducted by Jeanne Bishop in 1977 [1]. under the title *United States Astronomy Education: Past, Present and Future*. In this research she provides an overview of the field, curriculum development, and state of astronomy knowledge, referring to ideas and concepts of the public. As the highest priority, Bishop stated change of curriculum and teacher enhancement workshops. She emphasized how important the collaboration between teachers and scientists is in creating a new curriculum, which we still agree with today.

7.3.2 Studies related to the student's understanding of astronomy

One of the most well-known researches related to student understanding of astronomy was done by Philip Sadler [1], and this research was presented in a video called *A Private Universe* (Schneps, 1989). The video begins with a series of interviews with students and employees from Harvard University. Of the 23 people participating in the interviews, 21 could not provide a scientifically acceptable answer to the question of the cause of the seasonal changes or the phases of the Moon. The most common misconception given in the cause of the changes of the seasons was the changing distance between Earth and the Sun (that Earth is closer to the Sun in summer and further away during the winter). While the true answer to the Moon phase question encompasses the relative positions of the Sun, Earth And the Moon, the most common wrong answers would be explained by an "eclipse" or "interference" model.

Sadler also conducted the same survey on the 9^{th} grade students, which would suit the 1^{st} grade of high school in Croatian education system. The student presented in the video also did not understand the aforementioned concepts.

Perhaps not so well-known, but certainly of a more scientific nature was Sadler's 1992 Multiple Response Test that he developed as part of his dissertation work. This test tested the misconceptions found in the literature and during student interviews. With this research, Sadler noted that a large number of misconceptions (19 out of 51) were preferred by students instead of scientifically correct concepts [1].

Sadler's work directly affects and motivates most of the research conducted today.

Nussbaum & Novak conducted research in 1976 to find out students' misconceptions about the shape of the Earth, its position in the Universe, and how gravity affects the falling objects [1]. This research was done on 240 Israeli students, using the so-called Nussbaum scale:

- Level 1: The Earth is flat, and the sky and the Universe are above it
- Level 2: Earth is a ball. We live within Earth, and the sky is above us.
- Level 3: Earth is a ball. We live only at the top of the ball.
- Level 4: Earth is a ball. We live everywhere on Earth's surface, but bodies do not fall everywhere towards the center of Earth.
- Level 5: Earth is a ball, and the body falls everywhere towards its center. [31]

Using the same methods as Nussbaum & Novak, Mali & Howe conducted research in 1979 where they looked at the cognitive development of Nepali children [22].
Mali & Howe got the same results as Nussbaum & Novak, and concluded that the results were not geographically conditioned.
In 1994, Vosniadou and Brewer focused on a student's understanding of day/night cycles [1]. They analyzed the answers and concluded that the students had three general types of mental models:

- initial models, based on observation and experience and found predominately in younger children
- scientific models, which agree with current scientific theory to a high degree and are held only by a few of the oldest students
- synthetic models, where initial and scientific models are combined in an attempt to reconcile perceived differences between them, which are held by many older children

Vosniadou claims that students change their mental models in ways that allow them to retain as many as possible of their experimental beliefs without contradicting adult teachings. An example of a synthetic model that corroborates this theory is the belief that the Sun and the Moon, located on the opposite sides of the Earth, both revolve around Earth every day.

In 1989, Treagust & Smith explored the student's understanding of the concept of planetary motion. This study has resulted in several unexpected misconceptions such as that the rotation of the planet depends on the distance of the planet from the Sun and that the rate of rotation affects how much gravitational force the planet exerts on an object.

Kikas conducted the same research in the same group of students in 1998 and 2002 [1]. It has been shown that the students are able to describe the concepts that they had adopted just before the first test, which gave the illusion of their understanding of the astronomical concepts. As time went by, the students began to forget the terms, so Kikas wanted to emphasize the short-term memory of the students, that they use only for the needs of the test, and how this would not happen if the students actively participated in the classes.

7.3.3 The Astronomy Diagnostic Test

The Astronomy Diagnostic Test, ADT, is a standardized multiple choice test that studies the most common student misconceptions. This test uses student language instead of a scientific vocabulary. Although the faculty members view the questions as easy, students regularly perform poorly, suggesting well-chosen distractors [1]. An example of this test is available at: http://solar.physics.montana.edu/aae/adt/

7.3.4 Studies on Teacher Understanding

In the United States and other countries, studies of students' misconceptions have also led to research into the misconceptions of teachers regarding the understanding of astronomy concepts available to their students.

The first such research was carried out by Philip M. Sadler of Harvard-Smithsonian Center for Astrophysics and Alan Lightman of MIT in 1991 [1]. They studied how much the teachers are aware of the misconceptions students have before and after high school science or astronomy classes. The first research they carried out was related to the student's understanding of the Earth in space, based on the idea of students aged 13 and 14 that Earth is flat or that we all live within the Earth which is actually hollow [18], [20], [22], [23]. The level of understanding was based on Nussbaum's scale. For each grade, the average grade for both the teacher's prediction and student achievement was calculated. By carrying out this research, teachers at all levels overestimated the understanding and knowledge of their students. The biggest difference between expectations and outcomes was in the lowest grade. The research was conducted on 132 teachers and 330 students. Teachers asked for an expectation on the percentage of correct student response at the beginning and on re-testing at the end of astronomy or science classes. They then tested the students with an exam that consisted of 47 questions, of which teachers gave their predictions for 16 of them. Teachers on average have well anticipated student knowledge at the beginning of the lesson, but greatly overestimated the student's knowledge at the end. An interesting result of the research was that on some questions students had much worse achievements after class than before.

Another study was carried out by experts from Harvard-Smithsonian Center for Astrophysics in 2009 [26]. They constructed a test based on which they explored the student's understanding of the ideas from astronomy on three different levels. They were also interested in how well the teachers know and understand the concepts they teach, as well as the teacher's expectations of their student's understanding.

Research results have shown that teachers understand terms and concepts, but overestimate student achievements in the test.

From the results of these research we can conclude that teachers are not aware of student misconceptions and their ability to adopt a concept. Therefore, teachers do not decide to devote more time to developing a concept or applying another approach.

The cause of day/night cycles is one of those ideas. The teachers predicted 65% correct answers to the question on the first and 89% on the second test, but only half of that was achieved [31]. Students also have misconceptions related to the cause of the season changes. They attribute it to the change of Earth's distance from the Sun, in its rotation around the Sun. Their second idea is that the stars are closer to Earth than the planets, and they have no real image of the geometry and size of the basic celestial bodies. Another misconception is related to gravity. Some students think that there is no gravity in the Universe, and that the clusters of galaxies are held together by electromagnetism. Their misconception regarding the creation of the Universe is that the Big Bang created the Universe exactly as it is today. Many students also think that astronauts travelled far beyond the Moon's orbit.

7.4 Research in Croatian high schools

Research on misconceptions in Croatian high schools was done on the basis of tests from year 1991 [31] and 1999 [33]. This test was conducted in 3 Croatian high schools. It consists of 30 questions, out of which 23 of them are multiple choice questions and 7 of them are open type questions [26]. While constructing the multiple choice answers, special emphasis was put on a choice of distractors [26]. The educational outcomes sought by this test [26] were to:

- classify and describe the basic celestial bodies
- specify the relationships of the size, distance, and period of rotation of our close celestial bodies
- specify the order of magnitude of the age of the Universe, the Sun, and the Earth
- specify and describe the basic properties of the Sun and the Moon
- explain some basic phenomenon on Earth (day/night cycles, changes of the seasons, exchange of high and low tides)
- recognize and explain the observations of phenomena from the Earth, such as the Sun and Moon eclipse
- apply the law of gravity to bodies in the Universe
- apply Kepler's laws
- express and recognize the speed of light as the limiting speed of motion
- specify some properties of the Universe (most represented elements, temperature)
- describe the expansion of the Universe
- describe the Universe's existence through the Big Bang theory

The Ministry of Science, Education and Sports, in cooperation with the Education Agency and the Croatian Astronomical Society provides elementary and high school teachers with a list of common misconceptions in order to help them prepare their students for the annual astronomy competition:

- Seasons depend on the distance of Earth from the Sun
- Stars live forever
- All the stars are of the same color
- All the stars are lonely, far away from each other
- Meteors, asteroids and comets are different names for one and the same celestial body
- Shooting star is a star that really falls
- Comets burn, and in that process they realease gas
- The planet's orbits are circular
- We can see all sides of the Moon
- Only Moon causes tides
- The Sun has no influence on tides
- The Sun radiates mostly yellow light
- The Sun has a firm heated surface
- The Moon does not rotate around its axis
- The temperature of the Earth depends only on the distance from the Sun, not about the composition of the atmosphere
- The glow of stars in the sky corresponds to their true glow
- Sun is yellow
- What I see from the Earth's surface is the real radiation from the star
- Light travels at different speeds from different objects to us

(Astronomy competition, 2015)

7.4.1 Analysis of research results

As a result of this test [26], it was shown that the mean success in both the first and the fourth grade was below 50%. The difference between the results is only ≈5%. The question with the highest and lowest percentages of correct answers were the same ones in both age groups. Question with the lowest percentage of correct answers in both age groups prompted students to explain how we can determine the chemical composition of a star from Earth, while the question with the highest percentage of accurate answers prompted students to identify Sun as a star.

Regarding gravity in the Universe and Kepler's laws, students showed misconceptions in identifying gravity force with the acceleration of the gravity force. This is also one of the misconceptions I encountered while tutoring 1^{st} grade students. However this misconception cleared how students got older. The interesting and unexpected misconception encountered here was that some students consider Moon not to have gravitation at all (18% of the wrong answers in 1^{st} grade, and 28% in the 4^{th} grade [26]). Misconception exists, although it is not widely spread.
One of the biggest misconceptions was the one regarding Kepler's Laws, where 37% 1^{st} grade students answered correctly, although only 5 students gave partially correct explanation on why they choose this answer, while none of them gave completely correct explanation [26]. In 4^{th} grade 70% of the students choose correct answer and only 6 of them provided partially correct explanation and only 1 gave completely correct explanation [26]. It was shown that students attribute increase in tangential velocity of the planet, when it is closer to the Sun, to the increase of the gravitational force that the Sun exerts on the planet. From this question we can see lack of understanding in the role of the Sun's gravity force in planet's circular motion around the Sun.
Regarding the next group of questions that were probing student understanding of day/night cycle, change of the seasons as well as the concept of the high and low tide, some of the misconceptions were proved to be very strong. As well as in other countries, those misconceptions were related to the change of the seasons and cause of the high and low tide.
Only 15% 1^{st} grade and 12% 4^{th} grade students gave correct answer regarding the change of the seasons [26]. Students are convinced that change of the seasons de-

pends on the change of the Earth's distance from the Sun (83% of the 1^{st} grade and 90% of the 4^{th} students that gave the wrong answer [26]). The basis of this misconception lies in the fact that students know that the Earth's trajectory around the Sun is elliptic, but they think that this ellipticity is very distinct, and that the Earth's distance from the Sun greatly changes. Therefore, it seems to them that Earth is physically closer to the Sun in the summer than during the winter.

Interesting misconception that occurred in question that was trying to determine understanding of the cause of the high and low tide was that students addressed it to the Moon's magnetic field (90% of the wrong answers [26]). They explained that Moon's magnetic field is the one attracting the water on the Earth, so when the Moon is closer to the Earth, it is responsible for the low tide, and when it is further away from the Earth, it is responsible for the high tide. This distractor was chosen on purpose, since older research showed a similar misconception: "Galaxies are held together by electromagnetism, and not by gravity" [33].

The question of determining the chemical composition of the star from Earth has been a tough question for most students (only 6% partially correct answers in 1^{st} grade and 7% in 4^{th} grade [26]). A large number of students believe that the chemical composition of the stars can be determined by analysing comets and meteors that fall to the Earth. The reason for this misconception is that in the every day language for comets and meteors often is used the term "falling star". Therefore, students have the impression that comets and meteors are actually pieces of stars that fall, and that some of them end up on Earth. There is also the idea of a satellite that travels to the stars and collects samples that are later analysed on Earth. From this misconception we can also conclude that the students do not know the orders of magnitude for the temperature on the stars.

Next misconception was also related to the temperature of the stars. Students tend to believe that red stars have higher temperatures than the blue ones.

There is also a misconception that period of the Moon's rotation around the Earth is 24 hours, which is mainly based on the students observations $\rightarrow$ They see it during the night, so they assume it is not there during the day. They think that during the day it must be on the other side of the world, where there is currently night.

7.5 Implications for physics courses

Times are changing, technology is improving and science is only going forward so physics education must adapt to make it as efficient as possible. The first step is to completely replace the lecture-oriented style of teaching with an interactive inquiry based teaching. In planning and carrying out physics teaching, it is very important to be aware of the students' preconceptions and misconceptions. Only then teachers can induce the change in them. That gives the good basis and easier understanding for future knowledge gain. It is also important for teachers to be aware that the knowledge that students should acquire at school sometimes does not match the intuitive ideas formed in everyday life. Teachers should especially emphasize real life problems while explaining concepts related to physics.

Every new information is interpreted on the basis of past experiences, so if something does not fit into an existing student's mental model, it leads to the emergence of hybrid concepts. Therefore, it is extremely important during the preparation of the lessons to take into account possible student preconceptions and, based on them, to devise interactive methods that will be used to guide, direct and induce conceptual change. It is also important to go back and check mental models of students, or check if they are developing in the right direction and whether there are still difficulties. Throughout the year, concepts must be repeated and questioned. In this way, the number of student misunderstandings can be considerably reduced. There are various causes for misconceptions in astronomy. Some of these misconceptions are closely related to the misunderstanding of astronomical phenomena, while others point to the misinterpretation of physics and physical concepts themselves. These misconceptions should be suppressed by introducing changes in the teaching of physics itself and its structure.

In the teaching of physics in Croatian schools, the cause of the changes of the seasons, which we have noticed as a strong misconception, is not mentioned or explained in detail. In contrast, the planet's trajectory, including Earth's around the Sun, is mentioned several times. Thanks to this, students realize that the trajectory of the Earth around the Sun is elliptical, but it again leads to various misunderstandings, as mentioned before. It can be concluded that in schools it is not emphasized enough that this ellipticity can not be linked to the concept of the changes of the seasons. This misconception has been established for many years, both in Croatia and the rest of the world. In case teachers would have been aware of this issue, they could pay more attention to this phenomenon Still, we should have in mind that physics teachers in Croatia do not have enough time to teach topics outside the program, but there are still a few options.

One of the options would be to give this topic, as well as other misconceptions related topics, to students as independent work that they should shortly present to other students. The second option is to briefly emphasize, during the lesson, when it comes to the Earth's trajectory, that the Earth's elliptic trajectory around the Sun deviates from the circle by only 3%. This method could be applied to numerous situations. When covering the topic of *Light*, the teacher could briefly reflect on why winter is colder than the summer. Also, this concept relies on the the changes of the seasons, for which this would be a great opportunity to repeat and check the model. *The general law of gravitation* opens up much space for introducing and verifying astronomical concepts. Here, apart from Newton, the gravitational force and its role in the Universe, at the end of the lesson, we can deal with the problem of low and high tides, which also proved to be one of the major misconceptions of Croatian high school students. This topic, as well as the night/day and seasons cycle, is a part of the general knowledge, and as such should not be neglected in the school. It has been shown that a large number of students do not really understand what the centripetal force is and what its role is. When using circular motion in high schools, teachers can use an example of Earth and Satellite, in addition to the other every day examples such as car on the hill. In this case, it is necessary to identify which force has the role of centripetal force and then associate it with the Moon's movement around the Earth as well as the planets around the Sun.

When processing this topic, one can also mention the time needed for the Earth to make one turn around the Sun as well as the Moon's around the Earth. In the fourth grade of high school, when studying the *Spectral analysis*, its significance in astronomy can be emphasized, such as determining the chemical composition of a star.

My favourite techniques for inducing conceptual changes are Socratic Dialogue and Cognitive conflict. Unfortunately, these techniques would be more efficient if teachers would have enough time to do them properly. The only thing that would give teachers time to focus on some more important terms and concepts is the change in curriculum, which Croatian education system desperately needs.

7.6 Conclusions

In Croatia, as well as in the other countries, teachers often encounter student misconceptions. In classes related to astronomy, i.e. physics and other natural sciences, students are encountering terms and concepts from astronomy throughout their elementary school and high school education. Despite this, a large number of students still share the same misconceptions.

Astronomy and astrophysics are important branches of science. Nowadays, when technology advances every day, it is inadmissible for high school students to finish their high school education without the knowledge of basic terms and concepts related to the astronomical ideas.

The first and the basic step to achieve this goal would be to introduce the teachers to the student misconceptions. Combination of the teachers' awareness of students' misconceptions, change of the teaching approach from the lecture-oriented style of teaching to an interactive inquiry based teaching and inclusion of the students into the teaching process would give the best results. Only then, physics education can go in the right direction.

Literatura

[1] Bailey, J. M.; Slater, T.F. A Review of Astronomy Education Research // Astronomy Education Review. Vol. 2, (2004)

[2] Baldwin, J. A.; Phillips, M. M.; Terlevich, R. Classification parameters for the emission-line spectra of extragalactic objects // Astronomical Society of the Pacific, Publications. Vol. 93 (1981)

[3] Beckmann, V.; Shrader, C. R. Active Galactic Nuclei. Wiley-VCH Verlag GmbH, 2012.

[4] Brinchmann, J.; Charlot, S.; White, S. D. M.; Tremonti, C.; Kauffmann, G.; Heckman, T.; Brinkmann, J. The physical properties of star-forming galaxies in the low-redshift Universe // Monthly Notices of the Royal Astronomical Society. Vol. 351 4(2004)

[5] Brusa, M. et al. The XMM-NEWTON wide field survey in the COSMOS field. III: Optical identification and multiwavelength properties of a large sample of X-ray selected sources // COSMOS APJS Special Issue. (2007)

[6] Butler et al. // AA in press, arXiv170310296 (2017)

[7] Ciliegi, P.; Zamorani, G.; Hasinger, G.; Lehmann, I.; Szokoly, G.; Wilson, G. A deep VLA survey at 6 cm in the Lockman Hole // Astronomy and Astrophysics. Vol.398 (2003)

[8] Condon, J. J. The 1.4 gigahertz luminosity function and its evolution // Astrophysics Journal. Vol. 338, 1(1989)

[9] Condon, J. J. Radio emission from normal galaxies // Annual review of astronomy and astrophysics. Vol. 30 (1992)

[10] Desai, S.; Armstrong, R.; Mohr, J. J.; Semler, D. R.; Liu, J.; Bertin, E.; Allam, S. S.; Barkhouse, W. A.; Bazin, G.; Buckley-Geer, E. J.; Cooper, M. C.; Hansen, S. M.; High, F. W.; Lin, H.; Lin, Y.-T.; Ngeow, C.-C.; Rest, A.; Song, J.; Tucker, D.; Zenteno, A. The Blanco Cosmology Survey: Data Acquisition, Processing, Calibration, Quality Diagnostics, and Data Release // The Astrophysical Journal. Vol. 757 1(2012)

[11] Fotopoulou, S.; Pacaud, F.; Paltani, S.; Ranalli, P.; Ramos-Ceja, M. E.; Faccioli, L.; Plionis, M.; Adami, C.; Bongiorno, A.; Brusa, M.; Chiappetti, L.; Desai, S.; Elyiv, A.; Lidman, C.; Melnyk, O.; Pierre, M.; Piconcelli, E.; Vignali, C.; Alis, S.; Ardila, F.; Arnouts, S.; Baldry, I.; Bremer, M.; Eckert, D.; Guennou, L.; Horellou, C.; Iovino, A.; Koulouridis, E.; Liske, J.; Maurogordato, S.; Menanteau, F.; Mohr, J. J.; Owers, M.; Poggianti, B.; Pompei, E.; Sadibekova, T.; Stanford, A.; Tuffs, R.; Willis, J. The XXL Survey. VI. The 1000 brightest X-ray point sources // Astronomy Astrophysics. Vol. 592 (2016)

[12] Fuchs, R.; Vican, D.; Milanović Litre, I., Nacionalni okvirni kurikulum za predškolski odgoj i obrazovanje te opće obavezno i srednjoškolsko obrazovanje. Ministarstvo znanosti, obrazovanja i športa RH, Zagreb 2011. `http://mzos.hr/datoteke/Nacionalni_okvirni_kurikulum.pdf`

[13] Georgakakis, A.; Mobasher, B.; Cram, L.; Hopkins, A.; Lidman, C.; Rowan-Robinson, M. The Phoenix Survey: optical and near-infrared observations of faint radio sources // Monthly Notices of the Royal Astronomical Society. Vol. 306 3(1999)

[14] Gruppioni, C.; Mignoli, M.; Zamorani, G. Optical identifications and spectroscopy of a faint radio source sample: the nature of the sub-mJy population // Monthly Notices of the Royal Astronomical Society. Vol. 304 1(1999)

[15] Hales, C. A.; Murphy, T.; Curran, J. R.; Middelberg, E.; Gaensler, B. M.; Norris, R. P. BLOBCAT: software to catalogue flood-filled blobs in radio images of total intensity and linear polarization // Monthly Notices of the Royal Astronomical Society. Vol. 425 2(2012)

[16] Jauncey, D. L. Radio surveys and source counts // Annual review of astronomy and astrophysics. Vol. 13 (1975)

[17] Kauffmann, G.; Heckman, T. M.; Tremonti, C.; Brinchmann, J.; Charlot, S.; White, S. D. M.; Ridgway, S. E.; Brinkmann, J.; Fukugita, M.; Hall, P. B.; Ivezić, Ž.; Richards, G. T.; Schneider, D. P. The host galaxies of active galactic nuclei // Monthly Notices of the Royal Astronomical Society. Vol. 346 4(2003)

[18] Klein, C.A. Children's concepts of the Earth and the Sun: A cross cultural study // Science Education. Vol. 65 1(1982)

[19] Kron, R. G.; Koo, D. C.; Windhorst, R. A. A deep Westerbork survey of areas with multicolor Mayall 4 M plates. III - Photometry and spectroscopy of faint source identifications // Astronomy and Astrophysics. Vol. 146 1(1985)

[20] Lightman, A.; Sadler, P.M. How can the Earth be round? // Science and Children (1986)

[21] Longair, M. S. On the interpretation of radio source counts // Monthly Notices of the Royal Astronomical Society. Vol. 133, 421(1966)

[22] Mali, G.; Howe, A. Development of Earth and gravity concepts amongst Nepali children // Science Education. Vol. 64 2(1979)

[23] Nussbaum, J. Childrens' conception of the Earth as a cosmic body: a cross age study // Science Education. Vol. 63 1(1979)

[24] Obrić, M.; Ivezić, Ž.; Best, P. N.; Lupton, R. H.; Tremonti, C.; Brinchmann, J.; Agüeros, M. A.; Knapp, G. R.; Gunn, J. E.; Rockosi, C. M.; Schlegel, D.; Finkbeiner, D.; Gaćeša, M.; Smolčić, V.; Anderson, S. F.; Voges, W.; Jurić, M.; Siverd, R. J.; Steinhardt, W.; Jagoda, A. S.; Blanton, M. R.; Schneider, D. P. Panchromatic properties of 99000 galaxies detected by SDSS, and (some by) ROSAT, GALEX, 2MASS, IRAS, GB6, FIRST, NVSS and WENSS surveys // Monthly Notices of the Royal Astronomical Society. Vol. 370 4(2006)

[25] Padovani, P.; Miller, N.; Kellermann, K. I.; Mainieri, V.; Rosati, P.; Tozzi, P. The VLA Survey of Chandra Deep Field South. V. Evolution and Luminosity Functions of Sub-millijansky Radio Sources and the Issue of Radio Emission in Radio-quiet Active Galactic Nuclei // The Astrophysics Journal. Vol. 740 1(2011)

[26] Perković Kušić, T. Razvoj učeničkog razumijevanja astronomije kroz nastavu fizike. Diplomski rad. Zagreb : Prirodoslovno-matematički fakultet, 2015.

[27] Pozzetti, L.; Mannucci, F. Extremely red galaxies: age and dust degeneracy solved? // Monthly Notices of the Royal Astronomical Society. Vol. 317 1(2000)

[28] Prandoni, I.; Gregorini, L.; Parma, P.; de Ruiter, H. R.; Vettolani, G.; Zanichelli, A.; Wieringa, M. H.; Ekers, R. D. The ATESP radio survey. IV. Optical identifications and spectroscopy in the EIS-A region // Astronomy and Astrophysics. Vol. 369 (2001)

[29] Richards, E. A.; Fomalont, E. B.; Kellermann, K. I.; Windhorst, R. A.; Partridge, R. B.; Cowie, L. L.; Barger, A. J. Optically Faint Microjansky Radio Sources // The Astrophysical Journal. Vol. 526 2(1999)

[30] Rola, C. S.; Terlevich, E.; Terlevich, R. Physical Diagnostics of Emission-Line Galaxies in Deep Surveys // Revista Mexicana de Astronomia y Astrofisica Serie de Conferencias, Vol. 6 (1997)

[31] Sadler, P.M. Teachers' Misconceptions of their Students' Learning // The Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics, Misconceptions Trust., (1993)

[32] Sadler, E. M.; McIntyre, V. J.; Jackson, C. A.; Cannon, R. D. Radio Sources in the 2dF Galaxy Redshift Survey I. Radio Source Populations* // Publications of the Astronomical Society of Australia. Vol. 16 3(1999)

[33] Sadler, P.M.; Coyle, H.; Miller, J.L.; Cook-Smith, N. Dussault, M; Gould, R.R., The Astronomy and Space Science Concept Inventory: Development and Validation of Assessment Instruments Aligned with the K-12 National Science Standards // Astronomy Education Review. Vol. 8, (2010)

[34] Schinnerer, E.; Smolčić, V.; Carilli, C. L.; Bondi, M.; Ciliegi, P.; Jahnke, K.; Scoville, N. Z.; Aussel, H.; Bertoldi, F.; Blain, A. W.; Impey, C. D.; Koekemoer, A. M.; Le Fevre, O.; Urry, C. M. The VLA-COSMOS Survey. II. Source Catalog of the Large Project // The Astrophysical Journal Supplement Series. Vol. 172 1(2007)

[35] Smolčić, V.; Ivezić, Ž.; Gaćeša, M.; Rakos, K.; Pavlovski, K.; Ilijić, S.; Obrić, M.; Lupton, R. H.; Schlegel, D.; Kauffmann, G.; Tremonti, C.; Brinchmann, J.; Charlot, S.; Heckman, T. M.; Knapp, G. R.; Gunn, J. E.; Brinkmann, J.; Csabai, I.; Fukugita, M.; Loveday, J. The rest-frame optical colours of 99000

Sloan Digital Sky Survey galaxies // Monthly Notices of the Royal Astronomical Society. Vol. 371 1(2006)

[36] Smolčić, V.; Schinnerer, E.; Scodeggio, M.; Franzetti, P.; Aussel, H.; Bondi, M.; Brusa, M.; Carilli, C. L.; Capak, P.; Charlot, S.; Ciliegi, P.; Ilbert, O.; Ivezić, Ž.; Jahnke, K.; McCracken, H. J.; Obrić, M.; Salvato, M.; Sanders, D. B.; Scoville, N.; Trump, J. R.; Tremonti, C.; Tasca, L.; Walcher, C. J.; Zamorani, G. A New Method to Separate Star-forming from AGN Galaxies at Intermediate Redshift: The Submillijansky Radio Population in the VLA-COSMOS Survey // The Astrophysical Journal Supplement Series. Vol. 177 1(2008)

[37] Smolcic, V.; Delvecchio, I.; Zamorani, G.; Baran, N.; Novak, M.; Delhaize, J.; Schinnerer, E.; Berta, S.; Bondi, M.; Ciliegi, P.; Capak, P.; Civano, F.; Karim, A.; Le Fevre, O.; Ilbert, O.; Laigle, C.; Marchesi, S.; McCracken, H. J.; Tasca, L.; Salvato, M.; Vardoulaki, E. The VLA-COSMOS 3 GHz Large Project: Multiwavelength counterparts and the composition of the faint radio population // eprint arXiv:1703.09719 (2017)

[38] Sutherland, W.; Saunders, W. On the likelihood ratio for source identification // Monthly Notices of the Royal Astronomical Society. Vol. 259 3(1992)

[39] Veilleux, S.; Osterbrock, D. E. Spectral classification of emission-line galaxies // Astrophysical Journal Supplement Series. Vol. 63 (1987)

[40] Wall, J. V.; Pearson, T. J.; Longair, M. S. Models of the cosmological evolution of extragalactic radio sources. I - The 408-MHz source count // Monthly Notices of the Royal Astronomical Society. Vol. 193 (1980)

[41] Willott, C. J.; Rawlings, S.; Blundell, K. M. Extremely red galaxy counterparts to 7C radio sources // Monthly Notices of the Royal Astronomical Society. Vol. 324 1(2001)

[42] BPT diagram, `http://www.eso.org/~rfosbury/research/AGN2-07/exampleBPT.pdf`, 1.6.2017.

[43] Unified model of AGN, `http://astromev.in2p3.fr/sites/default/files/AGN_schematic_Beckmann_Shrader_2012.png`, 1.6.2017.

[44] Menanteau, F.; Hughes, J. P.; Jimenez, R.; Hernandez-Monteagudo, C.; Verde, L.; Kosowsky, A.; Moodley, K.; Infante, L.; Roche, N. Southern Cosmology Survey. I. Optical Cluster Detections and Predictions for the Southern Common-Area Millimeter-Wave Experiments // The Astrophysical Journal. Vol. 698, 2(2009)