

Radio Recombination Line Study of Ionized Gas in Nearby Starburst Galaxies

A Thesis
Submitted for the Degree of
Doctor of Philosophy
in the Faculty of Science

by
R. Niruj Mohan



Department of Physics
Indian Institute of Science
Bangalore 560 012 INDIA

October 2002

Declaration

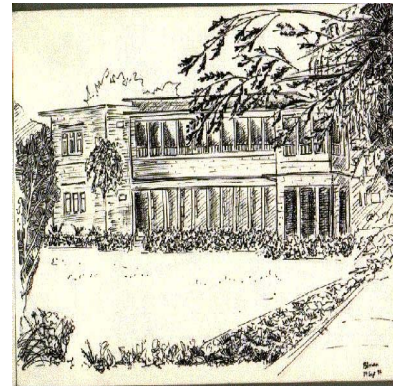
I hereby declare that the work reported in this thesis is entirely original. It was carried out by me at Raman Research Institute under the auspices of Joint Astronomy Program of the Department of Physics, Indian Institute of Science, Bangalore. I further declare that it has not formed the basis for the award of any degree, diploma, membership, associate-ship or similar title of any university or institution.

(R. Niruj Mohan)

17 October 2002

Department of Physics
Indian Institute of Science
Bangalore 560 012 India

Raman Research Institute
C.V. Raman Avenue
Bangalore 560 080 India



To Anantha ...

Acknowledgements

Though this is the only part of my thesis which would be read by anybody other than my hapless examiners, I had long thought that when it was my turn to write, I would stop at a perfunctory acknowledgement. However, it is my turn now, and I have decided to indulge myself and launch into pink, if not outright purple, prose. RRI would agree that this is a welcome change from the other pieces of prose which have been addressed to them in the past. However, no quotations, no poetry, no profound witticisms and lastly, no jokes about a PhD student, a software engineer and a sheep walking into a bar ...

It is of course customary to start with thanking ones supervisor, but for me, it is indeed a genuine pleasure to do so. When I started, I had no intention on working on radio astronomy and that too, on a fairly obscure subject like RRLs. It was solely because of my initial interactions with Anantharamaiah that both these fields acquired a life of their own and I decided to work with him for my thesis. Thinking back, I couldn't have made a better choice. I have learnt so much from him not only through numerous discussions, but also from his special way of looking at and solving problems. The freedom he has given me to learn things at my own pace and more importantly, to pursue different topics of interest on my own, is something I value enormously. Apart from the work presented here, he has encouraged me to explore other interests in radio astronomy. On the other hand, when he found me drifting, he has also set me back on track in his inimitable way. I am also thankful for having learnt what it is to work with a true expert in a subject. His encouragement and also his trust in my abilities, albeit misplaced, helped in pushing me to get this thesis done. People who knew him well would understand when I say he was also a unique person - always calm and polite, but also strict in his principles. I certainly haven't learnt any of his social skills, especially politeness, but I hope I have picked up atleast a bit of radio astronomy from him. His passing away on Oct 29th of 2001 is something I am still coming to terms with, and the last one year has been truly difficult. The strength with which he, and Jyotsna and Avi, coped with his illness during his last few months, however, will stay with me. I am indeed thankful for having had an opportunity, though limited, of working with him and cannot help but wonder at what might have been, if he was still here with us.

This thesis was saved from certain disaster last year by Biman Nath and Dwarakanath. Biman accepted the rather thankless job of supervising me in my final year and without him, I would probably still be working on chapter 1. His incredible patience, which I am sure I used up to a large extent, is truly appreciated. Thanks Biman. Dwaraka has been an unofficial guide to me ever since I joined RRI. Not only did he babysit me for a year when Anantha was away on a sabbatical, but subsequently, I have had as many discussions with him on my thesis work as I had with Anantha. Many a time have I barged into his office with a question and he has always been ready to spend time clearing my doubts.

Being a JAP student, joining RRI was probably the best thing to do - live in IISc and work at RRI, the best of both worlds. RRI is fairly unique among the various institutes - a quiet place, extremely well run, informal in its attitude and the lap of luxury. Its apparent lack of rules adds to its attributes. It has been a pleasure working in the astronomy department and getting to interact with the faculty and students on the floor. A thesis work depends heavily on various support services, rarely recognised. This thesis, done at RRI, owes its successful completion to the computer people, especially Jacob, to the library staff who maintain possibly the best run library in the country and are always ready to help beyond the call of duty, and Krishna and the superbly efficient admin, which rarely intrudes into ones life but makes sure everything runs smoothly. Us people on the RRI astro floor are a thoroughly pampered lot and

nothing illustrates this better than the kind of logistic support and office help provided by Ram till a few years ago and later by Vidya. Thanks also to the canteen staff for feeding me for the last five years, Lakshmamma for the daily coffee, and the transport section as well. RRI also provided me, along with others, with computers for our sole use, which was extremely useful during the past year. The course work done during the first year is supposedly one of the determining factors of ones research. IISc, RRI and IIA take enormous trouble in coordinating and organising the city-wide lectures, and my thanks to them. My thanks also to Arnab and Pijush for excellent courses and also to Arnab and Chanda for patiently handling all the JAP related administrivia. I also like to thank NCRA for time allotment and hospitality during my observing trips to the GMRT.

I would like to thank a number of people for discussions about various parts of this thesis, which have been of great benefit to me - specially Dwaraka, Dipankar, Shiv, Sunita, Bram, Aommar, Reks, Biman, Owen, Chanda, Desh, Manoj, Nimitz, Dipanjan, Prasad, JD, Mousumi, Rajaram, Kurtz, Ulvestad, Turner and Viallefond. 'My thesis' is certainly not an accurate phrase ! Most of the work in this thesis was done in collaboration primarily with Miller Goss. It has been an extremely interesting and eventful collaboration on my RRL work. I would like to thank him for the time he spent on my work, many discussions, and also the detailed attention he gave to any material I sent to him. Any skill I now claim to possess in writing and editing manuscripts, I owe totally to Miller. It has been a genuine pleasure working with Huub, Cimatti and Carilli. I would like to acknowledge many people who helped in some of the work presented here - Miller analysed the 330 MHz continuum data and also provided test time for some of the PKS 1830-211 observations, the idea of searching for RRLs from the latter objects was partly due to Ravi Subrahmanyam, some of my collaborators observed and analysed the NIR, mm and sub-mm data on EROs, Anish Roshi taught me how to observe with the ORT, and Nimisha, Jayadev and Dwaraka, among others, helped me with learning interferometry and also the AIPS software.

The observations carried out for this thesis work were done using the Very Large Array of NRAO (USA). It is truly remarkable that one of the world's largest and most sensitive radio telescopes is not only completely open to use by anyone in the world, without bias, but is also maintained such that it can be used remotely. Some of the work described in this thesis was done at the AOC, NRAO, USA. I thank both RRI and NRAO for the generous financial assistance towards this visit and NRAO for the wonderful hospitality. I also thank NRAO for page charge support for various publications. Part of the work was also carried out at the Leiden Observatory, Netherlands. I am grateful to the Netherlands Research School for Astronomy (NOVA), Leids Kerkhoven-Bosscha Fonds (LKBF) and Leiden Observatory for financial support and the Observatory and Huub Röttgering for the invitation and hospitality. This research has made use of NASA's Astrophysics Data System Abstract Service. This research has also made use of the NASA/IPAC Extragalactic Database (NED). The Starburst 99 code for population synthesis in starbursts has been used extensively and I thank the Starburst 99 team at STScI for sharing and maintaining this free simulation package. The freely available softwares ASURV and fivel have also been used in this thesis. I would like to thank Daniella Calzetti for providing me with the $H\alpha$ image of NGC 5253, Torsten Böeker for the [NeII] image of NGC 253 and Chris Carilli for the wide field continuum images of NGC 253 at 8.3 GHz and 330 MHz.

I had initially wondered as to why people acknowledge friends and other non-academic interests in their thesis. Over the years I have come to realise why – doing a PhD is an insane enough task by itself and hence the right kind of social support not only prevents mass homicides in educational institutions, but any thesis also owes directly to such support structures. Apart from the thesis, the one other major thing I did during the last six years was to come

out. Considering what a potentially traumatic experience it could have been, to myself and also for my thesis, I am extremely thankful and lucky to have a set of friends who were incredibly supportive throughout, especially when I would talk about nothing else for months on end. My various fears and anxieties during the initial few months were put to rest by, among others, Raja, Dandy, Kheya, Wouter, Apte, Anu(p) and Manoj. All of my other friends at IISc, RRI and at Socorro are also owed a lot in this regard. I also managed to come out to Anantha, who was amazingly supportive in his reaction. So also the rest of the astro faculty at RRI.

Not only did I have fun with a whole lot of friends at the two institutes, I am also glad to have gotten to know people outside these institutes, who provided an escape whenever I grew too tired of my twin wombs of IISc and RRI. And with that ends my ability to construct whole sentences in english. I would like to mention now, at a stretch, various people and things who made my life interesting – Ratna for providing me with much needed degenerative culture, a tragedy it closed down and a pox on its new occupants; every pub in town I have diligently been on pilgrimages to, even on crutches; my friends who took me gallivanting around town when I had broken my leg; people who gave unsolicited advice when I ingested parts of writing implements; strand and premier which saved me from ranade; oldmonk (my all-round saviour, my comp and me); mahalaxmi dhaba, hallowed be thy cook; sangama and the thursday place (hope they acquire a mentionable acronym soon) for their support as well as all their attendant drama; assorted queens; Wouter, for putting me up at Leiden; Ron for listening to my fundae over the years; Dandy, Sumana for being good friends and giving me a patient hearing whenever I felt like cribbing; Balu, the tum minus δ , for all those endless debates; Moyna for rum-cakes and conversation; Shady for living up to her name; Tobs the holymalluterror for the palghat peg among other things; Raghu for his advice on all matters medical and also for an amazing display of egg-juggling; Arti for actually letting him do so in her room and for patient hearings-out; Sandeep for good drinking company; Osho, for fantastic company at odd places and odd hours and for being a nasty fairy godmother; qbc; chinlung; narrain, boy, boy and narrain for providing much needed alternative company; Kheya, my best f.h., and all-purpose shoulder; Jyotsna, Chitra and Usha whom I got to know through RRI and later became good friends with, Jyotsna and Chitra specially for all the lovely grub; Maddy who kept prodding me to get work done; various students at RRI who have made my six year stay less painful - Reks, my computer guru, also the institute superstud; Nadeem, who is an even better one; Sups who contributed to my moral degeneration but also contributed tea, along with Csg; Ami-tomar of the Sawai Jai Singh fame; Sushil and Dipanjan for intended humour; Ashish for the unintended ones; Shiv, a thoroughly bad influence on me; Sunita, who was my break from work; Rema, who gladly shares my cynicism; Sushan, in loco parentis; Mala, who was just incredible fun; my seniors Indra, Nimitz and JD; Resmi, Rajesh, Pandey, Jumper and other RRI junta who kept asking me about my thesis, hoping I would finish and depart; Manoj and other friends at IIA, too numerous to mention; all my bacche log whom I seem to acquire at a steady rate; and lastly, the RRI internet filter for valiant attempts at restoring my morals and building my character.

Finally, I would like to end by acknowledging my debt to both K. K. Ghosh and Devadas for encouraging me to pursue Astronomy. Also to my parents who have always supported me in doing what I wanted and never forced upon me their ideas of what a proper career ought to be.

Contents

1	Introduction	1
1.1	Starburst Galaxies	1
1.1.1	The starburst phenomenon	1
1.1.2	Stars and the ISM in starburst galaxies	6
1.2	Radio emission from galaxies	12
1.2.1	Radio continuum	13
1.2.1.1	Synchrotron emission	13
1.2.1.2	Thermal emission	13
1.2.2	Radio recombination lines (RRLs)	14
1.2.2.1	RRL – line formation and transfer	15
1.2.2.2	RRLs under <i>LTE</i> conditions	17
1.2.2.3	RRLs under non- <i>LTE</i> conditions	18
1.3	RRLs from starburst galaxies	22
1.3.1	Past work	22
1.3.2	Motivation for our observations	24
2	Observational strategy and the RRL modelling procedure	27
2.1	Description of telescope used : Very Large Array (VLA)	27
2.2	Observations	28
2.2.1	Search for RRLs from nearby starburst galaxies	30
2.2.2	Multi-line observations of selected galaxies	31
2.2.3	Data analysis	32
2.3	RRL modelling	34
2.3.1	Single-density models	36
2.3.2	Multi-density models and the single-density approximation	38
2.3.3	Determining the solutions space of the models	40
3	NGC 253 : high-resolution multi-line observations	42
3.1	Introduction	42
3.2	Observations	44
3.2.1	Observations at 1.4 GHz	44
3.2.2	Observations at 8.3 GHz and 15 GHz	47
3.3	The radio nucleus	56
3.3.1	Modelling the ionized gas	56
3.3.2	Ionizing source	58
3.3.2.1	A compact SNR as an ionizing source	59

3.3.2.2	A star cluster as an ionizing source	60
3.3.2.3	A weak AGN as an ionizing source	64
3.3.3	Summary and Discussion	67
3.4	Extended RRL emission	67
3.4.1	The continuum images	68
3.4.2	The H92 α line images	70
3.4.3	Properties of the ionized gas	75
3.4.3.1	Large scale emission	75
3.4.3.2	Extranuclear compact sources	79
3.4.3.3	‘15 pc region’	82
3.4.3.4	Modelling the 1.4 GHz line emission: multi-density gas . . .	84
3.4.4	Discussion	86
3.5	Summary and Conclusions	91
4	NGC 5253 and Henize 2-10 : blue compact dwarf galaxies	93
4.1	Introduction	93
4.2	Observations	94
4.3	Modelling the ionized gas properties	95
4.4	Super-star Clusters	98
4.4.1	Results from the low-resolution RRL data : NGC 5253	98
4.4.2	Results from the low-resolution RRL data : He 2-10	98
4.4.3	Compactness of the RRL emission : NGC 5253	100
4.4.4	Compactness of the RRL emission : He 2-10	101
4.5	Properties of the ‘supernebulae’	102
4.6	NGC 5253 and the radio-FIR correlation	104
4.7	Summary	106
5	NGC 3628 and Arp 299: multi-line observations	107
5.1	Introduction	107
5.2	Observations	108
5.3	Modelling the ionized gas	111
5.3.1	NGC 3628	112
5.3.2	IC 694	116
5.3.3	NGC 3690	117
5.4	Discussion	118
5.5	Summary	120
6	Search for H92α line emission from nearby starbursts	122
6.1	NGC 4038/9 (Antenna galaxies)	122
6.1.1	Introduction	122
6.1.2	Observations and results	122
6.1.3	Modelling the ionized gas	123
6.2	NGC 1808	125
6.2.1	Introduction	125
6.2.2	Observations and results	126

6.2.3	Modelling the ionized gas	127
6.2.3.1	The hotspot in NGC 1808	128
6.2.3.2	Nucleus and surrounding star forming sites in NGC 1808 . . .	131
6.3	II Zw 40	131
6.3.1	Introduction	131
6.3.2	Observations and Results	132
6.3.3	Modelling the ionized gas	132
6.4	NGC 7552	133
6.4.1	Introduction	133
6.4.2	Observations and results	133
6.4.3	Modelling the ionized gas	134
6.5	VV 114	134
6.5.1	Introduction	134
6.5.2	Observations and results	135
6.5.3	Modelling the ionized gas	135
6.6	Discussion	135
6.6.1	Correlations between the H92 α emission and SFR tracers	135
6.6.2	Detectability of line emission from nearby galaxies	138
6.6.2.1	Gas density of proto-SSC molecular clouds	140
6.6.3	RRL emission as a tracer of the SFR history of a galaxy	141
6.7	Summary	144
7	The gravitational lens system PKS 1830-211	146
7.1	Introduction	146
7.2	Observations	147
7.2.1	Single-epoch radio continuum spectrum	147
7.2.2	Observations of H158 α and H136 α RRLs	148
7.3	Modelling the ionized gas	149
7.4	Discussion	149

Bibliography	151
---------------------	------------

List of Figures

1.1	b_n vs. n for various densities	19
1.2	β_{mn} vs. n for various densities	19
1.3	Non- <i>LTE</i> to <i>LTE</i> line ratio vs. frequency for EM= 10^7 pc cm $^{-6}$	20
1.4	Non- <i>LTE</i> to <i>LTE</i> line ratio vs. τ_c for various densities	21
1.5	Non- <i>LTE</i> RRL power vs. n_e for various lines	22
2.1	Minimum detectable EM vs. ν for free-free emission using the VLA	28
2.2	Minimum detectable EM, n_e vs. l for RRL emission using the VLA	29
2.3	Minimum detectable EM vs. ν for RRL emission using the VLA	30
2.4	H92 α /H75 α and H92 α /H65 α flux ratios vs. n_e for various EM	35
2.5	A cartoon of Models I, II and III for the ionized gas	37
2.6	H92 α intensity vs. n_e for constant EM and constant $N_{\text{Ly}\alpha}$	39
3.1	1.4 GHz continuum images of NGC 253 in C and B configurations.	46
3.2	H166 α and H168 α spectra towards NGC 253	47
3.3	8.3 GHz continuum image of NGC 253 in A configuration	48
3.4	15 GHz continuum image of NGC 253 in A configuration	49
3.5	The H92 α line emission overlayed on radio continuum emission	50
3.6	Channel images of H92 α emission from central 25 pc of NGC 253	52
3.7	H92 α spectrum towards the four extranuclear sources in NGC 253	54
3.8	The integrated H92 α line spectrum towards the 15 pc region	55
3.9	Channel images and spectra of H75 α emission	55
3.10	Model predictions for continuum and line for nucleus of NGC 253	58
3.11	R_s and V_s vs. t for a solution in the SSC model of the NGC 253 nucleus	63
3.12	1.4 GHz continuum images of NGC 253 - circumnuclear compact sources	69
3.13	Integrated H92 α line emission from the central 15 pc region	73
3.14	H92 α spectra towards three of the sources in the 15 pc region	75
3.15	Low resolution integrated line flux vs. frequency	76
3.16	H166 α -H40 α spectral index vs. n_e and EM (LTE and non-LTE)	77
4.1	8.3 GHz continuum images of NGC 5253 and He 2-10.	94
4.2	The H92 α spectra of NGC 5253 and He 2-10.	96
4.3	Predicted continuum and RRL strengths for NGC 5253 and He 2-10	97
5.1	15 GHz, 1.4 GHz and 0.33 GHz continuum images of NGC 3628	110
5.2	15 GHz, 1.4 GHz and 0.33 GHz continuum images of Arp 299	111
5.3	Spectra of H75 α towards NGC 3628 and IC 694 and H166 α towards IC 694	112

5.4	Model predictions for continuum & line emission for nucleus of NGC 3628 . .	114
5.5	Model predictions for continuum & line emission for nucleus of IC 694	116
5.6	Model predictions for continuum & line emission for nucleus of NGC 3690 . .	117
6.1	8.3 GHz continuum images of NGC 4038/9	123
6.2	8.3 GHz continuum image of NGC 1808	128
6.3	H92 α spectrum towards hotspot in NGC 1808	129
6.4	Model predictions for continuum and line for hotspot in NGC 1808	130
6.5	8.3 GHz continuum images of II Zw 40 and VV 114	131
6.6	8.3 GHz continuum images of NGC 7552	133
6.7	Flux-flux correlations between radio, FIR and H92 α emissions	136
6.8	Luminosity-luminosity correlations between radio, FIR and H92 α emissions . .	137
6.9	H40 α , H92 α and H166 α line flux densities as a function of θ and D	139
6.10	H40 α , H92 α and H166 α line flux densities <i>vs.</i> time for an overpressured HII region	142
6.11	RRL flux density <i>vs.</i> frequency for various values of t and n_o	144
7.1	Single-epoch radio continuum spectrum of PKS 1830-211	148
7.2	Maximum EM <i>vs.</i> n_e for the 2 lens galaxies in PKS 1830-211	150