

Chapter 6

Search for H92 α line emission from nearby starbursts

Five nearby starburst galaxies (NGC 4038/9, NGC 1808, II Zw 40, NGC 7552 and VV 114) were observed at 8.3 GHz using the VLA to search for H92 α line emission. The criteria used in the selection of this sample of galaxies, along with NGC 5253 and He 2-10, are described in detail in section 2.2.1. Of the five galaxies discussed here, recombination line emission is observed only in NGC 1808, from a compact off-nuclear continuum source. The observations, galaxy properties and the ionized gas models are described in this chapter (the assumed distance to each galaxy corresponds to $H_0=75 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

6.1 NGC 4038/9 (Antenna galaxies)

6.1.1 Introduction

Arp 244 ($D=21 \text{ Mpc}$) is an infrared luminous object, consisting of two interacting galaxies, NGC 4038 and NGC 4039. The entire system is undergoing a vigorous starburst. The interaction between the two galaxies has given rise to extended tidal tails, seen in the optical and in HI (Hibbard et al. 2001 and references therein), and hence Arp 244 is also called the Antennae, due to its visual appearance. Numerous star clusters, including super star clusters, have been detected and studied in detail in this system (Whitmore & Schweizer, 1995; Whitmore et al., 1999). The peaks of emission in molecular (Stanford et al., 1990), radio (Hummel & van der Hulst, 1986), MIR (Vigroux et al., 1996; Mirabel et al., 1998) and mm (Evans, Harper & Helou, 1997; Bushouse, Telesco & Werner, 1998; Haas et al., 2000) all lie in an optically obscured overlap region between the nuclei of the two galaxies, and is the site of most of the star formation in Arp 244. Neff & Ulvestad (2000; hereafter NU00) imaged the multi-frequency radio continuum emission in this galaxy at high resolution ($1''$ - $2.6''$) and identified a host of compact sources, some of which are observed to exhibit a flat spectral index.

6.1.2 Observations and results

Arp 244 was observed using the VLA in the C and DnC configurations to search for the H92 α line. The combined datasets were used to make the final images. The observational parameters are summarised in table 6.1. The continuum images, made using the two individual datasets, are shown in figure 6.1. The flux densities of various compact sources are consistent with those

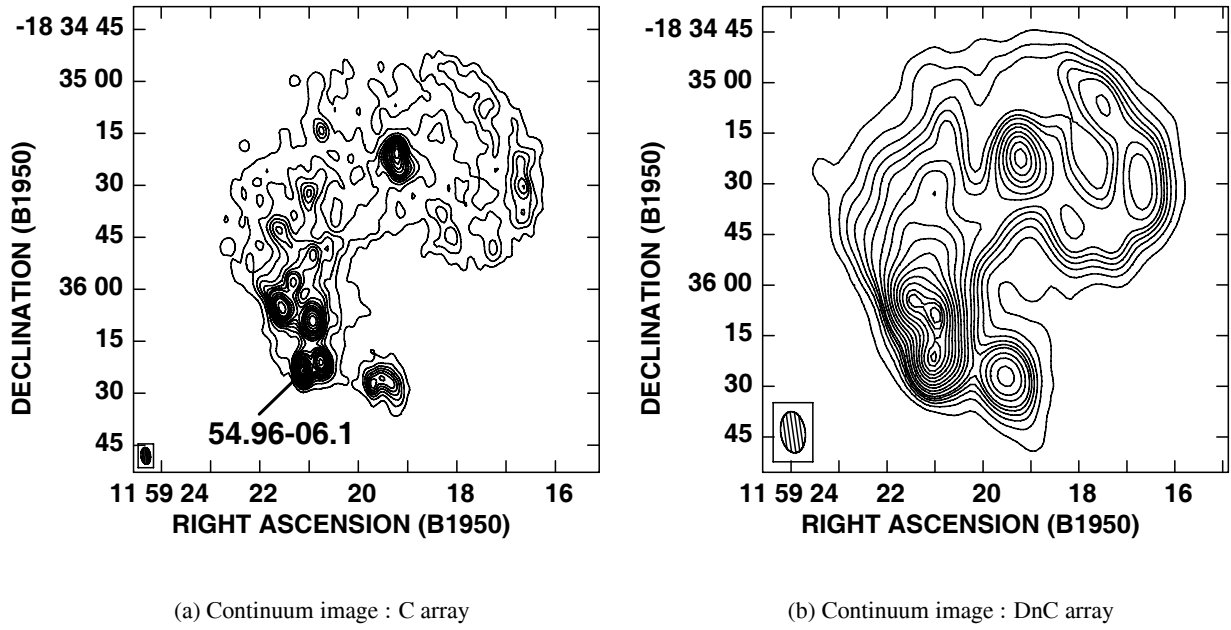


Figure 6.1: 8.3 GHz continuum image of NGC 4038/9 using **(a)** C configuration. The rms noise in the image is $25 \mu\text{Jy/beam}$ and the contour levels are (5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 100, 120, 140, 160, 180, 200) $\times$ rms in image. The synthesized beam is $4.8'' \times 2.7''$ at a P.A. of 7° ; **(b)** DnC configuration. The rms noise in the image is similar ($22 \mu\text{Jy/beam}$) and the contour levels are (10, 20, 30, 40, 50, 60, 80, 100, 130, 160, 200, 240, 280, 320, 360, 380, 400) $\times$ rms in image. The synthesized beam is $12.3'' \times 7.2''$ at a P.A. of 8° .

derived by NU00. Line emission is not detected towards any of the compact sources. The rms noise in individual channel images is $60 \mu\text{Jy/beam}$. Assuming a line width of 110 km s^{-1} , the 3σ upper limit to the H 92α line emission is $0.47 \times 10^{-23} \text{ W m}^{-2}$.

6.1.3 Modelling the ionized gas

NU00 have listed the 4.8 GHz and 8.3 GHz flux densities of thirteen sources which exhibit a spectral index α flatter than -0.4 ($S_\nu \propto \nu^\alpha$), which they interpret as indicating a high thermal gas fraction. They derive the rms electron density for resolved sources and also lower limits to the density for the unresolved sources. We use the upper limits to the H 92α line emission in order to further constrain the properties of the strongest thermal source *54.96–06.1* which is indicated in the figure. NU00 determined the diameter of this source to be 70 pc ($0.7''$) and hence derived an rms density of $\sim 400 \text{ cm}^{-3}$. We model this source as a collection of uniform density spherical HII regions. The fraction, f_{th} , of the total 8.3 GHz continuum flux density $S_c = 4.7 \text{ mJy}$ measured by NU00, which is due to thermal emission, is introduced as a free parameter. The model solutions are constrained to produce a 8.3 GHz free-free emission equal to $f_{\text{th}} \times S_c$ and a H 92α line emission which is less than the observed upper limit. The spectral index between 4.8 GHz and 8.3 GHz is constrained to be consistent with the observed value, especially for those models where f_{th} is close to unity. NU00 estimate an FIR luminosity of this source of $1.3 \times 10^{43} \text{ ergs s}^{-1}$. Using this value for L_{FIR} , we also constrain the InfraRed Excess (IRE), defined as $L_{\text{FIR}}/N_{\text{Lyc}}$, to be greater than unity. No solutions are obtained for $f_{\text{th}} > 0.6$ if the

Table 6.1: Observational and image parameters of NGC 4038/9, II Zw 40, NGC 7552 and VV 114

Parameter	NGC 4038/9		II Zw 40	NGC 7552		VV 114
	C	DnC		CnB	D	
Date of observation	27/12/98	20/2/99	14/8, 29/9/00	16/11/98	23/4/99	3/4/99
ν_{rest} of RRL (GHz)	8309.38	8309.38	8309.4, 8045.6	8309.38	8584.8	8309.38
Bandwidth (MHz), channels, IF	23.44, 15, 2	23.44, 15, 2	23.4, 15, 2	46.9, 15, 1	46.9, 15, 1	23.4, 15, 2
Spectral resolution ^a (km s ⁻¹)	113.4	113.4	113	226	226	115
Minimum baseline (k λ)	2.0	1.3	0.95	2.6	2.5	0.8
Synthesized beam (natural weighting)	4.8'' $\times$ 2.7''	12.3'' $\times$ 7.2''	11.9'' $\times$ 11.7''	5.1'' $\times$ 2.5''	31.4'' $\times$ 6.7''	16.0'' $\times$ 10.0''
P.A. of beam (°)	7	8	-11	11	-3	18
Phase calibrator (B1950.0)	1127-145	1127-145	0530+135	2311-452 & 2227-394	2311-452	0113-118
Bandpass calibrator (B1950.0)	1127-145	1127-145	0530+135 & 3C 48	2255-282 & 3C 48	2255-282	0113-118
Peak continuum (mJy/beam)	5.08	9.13	13.4	13.6 ^b	40.2	27.3
Total continuum (mJy)	123	128	20	55	55	54
Noise in continuum image (1 σ , μ Jy/beam)	25	22	20	33	45	23
Noise per channel (μ Jy/beam)	66	68	56	80	135	56
Line strength ^c (3 σ , $\times 10^{-23}$ W m ⁻²)	<0.47		<0.6	<0.76		<0.57

^aAfter offline Hanning smoothing.

^bThe peak continuum strength for sources A & B is 11.5 mJy/beam and for C & D is 13.6 mJy/beam in the CnB image.

^cAssuming an FWHM equal to the velocity resolution of the data.

RRL constraint is included. The derived values for the gas density and the size of the HII region vary between 5×10^2 to 10^4 cm^{-3} and 40 to 5 pc, respectively. The value of IRE is between 6-10. The predicted H92 α line strength is 80-100 % of the 3σ upper limit if the thermal fraction is not less than 0.3 and hence might be detectable with slightly more sensitive RRL observations. NU00 derive a spectral index of -0.26 ± 0.13 between 4.8 GHz and 8.3 GHz. Hence, since $f_{\text{th}} < 0.6$, there are two possibilities. There could be an additional component of ionized gas in this source which is at a density much different from the value derived by us, and produces negligible line emission at 8.3 GHz. Else, the continuum emission from this source is not purely thermal and is definitely mixed with some amount of non-thermal emission. In order to yield a spectral index as flat as -0.26 , the thermal and non-thermal gas must be mixed in a complicated geometry.

Arp 244 has one of the highest star formation rate densities known among nearby ULIGs. Based on the large number of super star clusters, the strong mid IR emission and the amount of molecular gas, it is also known that star formation is currently ongoing in this system at a high rate. Hence it is surprising that we do not detect RRL emission from this galaxy. Since it is unlikely that the starburst has declined rapidly over the last million years or that the average gas density in Arp 244 is far less than in other starburst systems, the most likely reason for the non-detection is probably the rather large angular scale over which the star formation is going on. Hence a search for RRLs at much lower resolution, possibly using the GBT, might prove more fruitful.

6.2 NGC 1808

6.2.1 Introduction

NGC 1808 (D=11 Mpc) is a spiral galaxy (Sbc pec) undergoing a starburst, with an FIR luminosity of $2 \times 10^{10} L_{\odot}$. Apart from a bright nucleus, this galaxy exhibits a bar, several optical hotspots (Sersic & Pastoriza, 1965) and dusty radial filaments over the central few kpc (Veřon-Cetty & Veřon, 1985). The peculiar morphology and the starburst activity are attributed to tidal interactions with the companion NGC 1792 (Dahlem et al., 1990). HI observations show a strong outflow (Koribalski, et al., 1993), co-spatial with the dusty filaments. There is evidence both for and against Seyfert activity at the nucleus (Forbes, Boisson & Ward, 1992; Kotilainen et al., 1996). CO and HI imaging (Dahlem et al., 1990; Koribalski, Dickey & Mebold, 1993; Koribalski et al., 1996) show a central concentration of gas surrounded by a $\sim 25''$ rotating molecular ring, believed to be coincident with the Inner Lindblad Resonance of the kpc-scale bar. There is also evidence for non-circular gas motion (Saikia et al., 1990). The central kpc is seen to consist of a population of compact sources in high resolution radio continuum images (Saikia et al., 1990; Collison et al., 1994). NIR continuum and line imaging at $1.8''$ (Krabbe, Sternberg & Genzel, 1994) and $1.0''$ (Kotilainen et al., 1996) show a number of Br γ , [FeII] and H $_2$ knots. The Br γ and radio continuum knots are spatially correlated at a resolution of $1.8''$ but are not exactly coincident at a higher resolution of $1.0''$. There is no correlation between the positions of the optical hotspots and the radio/Br γ knots, hence the former seem to trace regions of low dust extinction rather than regions of star formation. Most of the radio knots have a steep spectral index and are probably SNRs, with a thermal fraction not exceeding ~ 30 % at cm-wavelengths. Using spectrophotometric models, Krabbe, Sternberg & Genzel (1994) and

Kotilainen et al. (1996) derive an age $>40\text{--}50$ Myr for the nuclear starburst and much younger ages of less than $10\text{--}15$ Myr for the circumnuclear hotspots. Tacconi-Garman, Sternberg & Eckart (1996) imaged the galaxy in the NIR K band at $0.6''$ resolution and detected a number of unresolved sources, believed to be young massive SSCs. Assuming a decaying SFR, they derive ages similar to the earlier work for the nucleus and the hotspots. However, they also derive a much larger age of ~ 200 Myr for all of the sources assuming a history of continuous star formation.

6.2.2 Observations and results

NGC 1808 was observed in the CnB and DnC arrays of the VLA to search for the $\text{H}92\alpha$ RRL at 8.3 GHz. The observational parameters are given in table 6.2. The continuum images made with the two datasets are shown in figure 6.2. The C array image (using natural weighting) has a resolution of $3.6'' \times 2.5''$ and hence does not resolve all the continuum knots detected by Saikia et al. (1990). However, it is consistent with the 1.4 GHz continuum image of Saikia et al. (1990) which is of similar resolution.

The brightest continuum source seen in figure 6.2a is the nucleus, and the second brightest, labelled as ‘Hotspot’ in the figure, can be seen in the 1.4 GHz image of Saikia et al. (1990) as well. Based on the 1.4 GHz and 8.3 GHz continuum fluxes measured with a $\sim 3''$ beam, the spectral indices of the nucleus and the hotspot are calculated to be -0.57 and -0.65 respectively. Higher resolution images show that the hotspot consists of two compact distinct sources. These are referred to as A10 and A11 by Collison et al. (1994). Though diffuse $\text{Br}\gamma$ emission is seen in a region encompassing both sources, only a single $\text{Br}\gamma$ knot is seen in this region and it lies very close to A10 (Krabbe, Sternberg & Genzel, 1994; Kotilainen et al., 1996). Hence there seems to be larger amounts of thermal gas towards A10 compared to A11, even taking into account dust extinction. The radio continuum emission from A10 is weaker than the emission from A11 in the high resolution images with subarcsecond resolution. However, images at a lower resolution of about $3''$ at 8.3 GHz (this work) and 1.4 GHz (Saikia et al., 1990) show that the smoothed emission peaks much nearer the position of A10, indicating the presence of substantial diffuse emission around this source.

Table 6.2: Observational and image parameters of NGC 1808

Parameter	NGC 1808	
	CnB array	DnC array
Date of observation	10/11/1998	18/02/1999
ν_{rest} of RRL (GHz)	8309.38	8309.38
Bandwidth (MHz), channels/IF	46.9, 15	46.9, 15
Spectral resolution ^a (km s ⁻¹)	226	226
Minimum well-sampled baseline (k λ)	3.8	1.2
Synthesized beam (natural weighting)	3.6'' $\times$ 2.5''	11.3'' $\times$ 8.2''
P.A. of beam	-6°	-8°
Phase & Bandpass calibrator (B1950.0)	0402-362	0402-362
Peak 8.3 GHz continuum (mJy/beam)	19.6	56.6
Total 8.3 GHz continuum (mJy)	110	121
Noise in continuum image (1 σ , μ Jy/beam)	35	33
<i>Hotspot parameters using C array data</i>		
Peak 8.3 GHz continuum (mJy/beam)	7.0	
Peak 1.4 GHz continuum ^b (mJy/beam)	22.4	
Peak line flux density (mJy/beam)	0.30 $\pm$ 0.08	
Measured FWHM (km s ⁻¹)	335 $\pm$ 75	
Line strength ($\times 10^{-23}$ W m ⁻²)	3 $\pm$ 1	

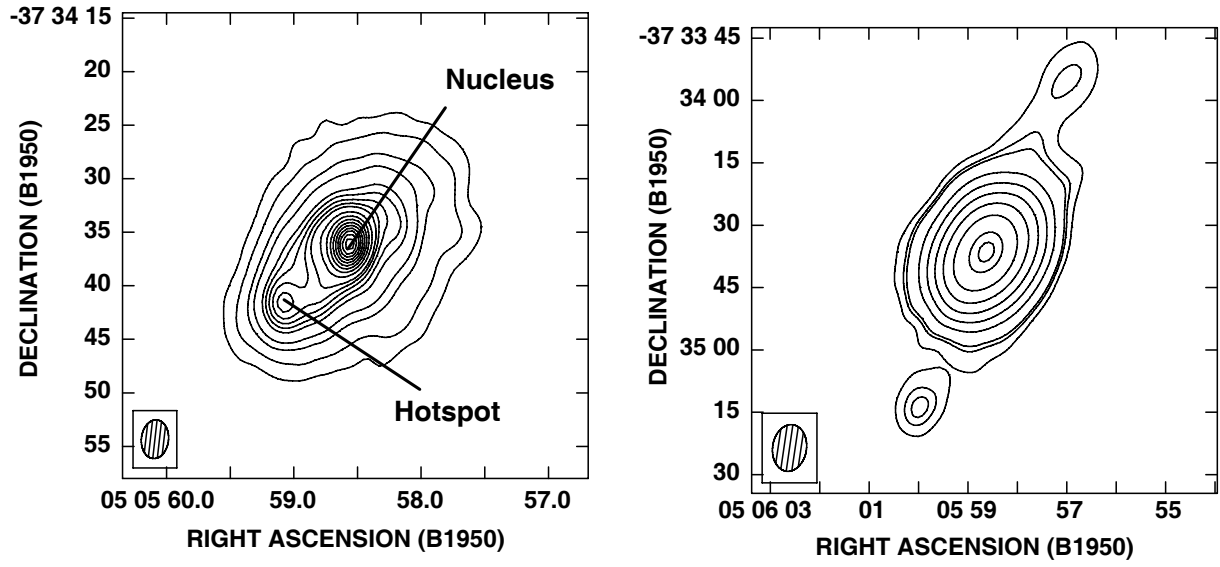
^aAfter offline Hanning smoothing.

^bSaikia et al. 1990.

Line cubes were obtained for the CnB and DnC configuration data separately. Line emission is detected only towards the hotspot in the C configuration data, whereas no emission is detected in the lower resolution D configuration data. The former shows that the line emission is localised and hence might be beam diluted when observed at lower resolution. If the H92 α line flux from the other star forming sites in the galaxy are much below the rms noise level, then beam dilution is probably the reason why we do not detect the line in the DnC configuration dataset. The spectrum of the H92 α line towards the hotspot is shown in figure 6.3. The line emission extends between ~ 900 – 1300 km s⁻¹. The shoulder observed at lower velocities is identified as noise since the line flux in this velocity range is within 1σ . The systematic enhancement of the line emission in this velocity range, therefore, could reflect incorrect subtraction of the continuum baseline. It should be noted that the rms in the channel images is $97 \mu\text{Jy/beam}$ and hence the peak line emission is only 3σ . Therefore this line feature needs to be further confirmed. The observed FWHM of the line is 336 ± 75 km s⁻¹ and the deconvolved line width, after correcting for offline Hanning smoothing and finite spectral resolution, is about 210 km s⁻¹. Assuming that the intrinsic width of line emission from the other Bry knots is about 100 km s⁻¹, the 3σ upper limit to the H92 α emission from these sources is 1×10^{-23} W m⁻².

6.2.3 Modelling the ionized gas

It is noteworthy that though the central region of NGC 1808 consists of a number of starburst sites, the H92 α line emission is detected only from the hotspot SE of the nucleus. Bry emission is observed from the hotspot, the nucleus and also from some of the circumnuclear regions. The hotspot is not the brightest source in Bry and is, in fact, comparable in the line intensity to



(a) 8.3 GHz CnB configuration continuum image of NGC 1808

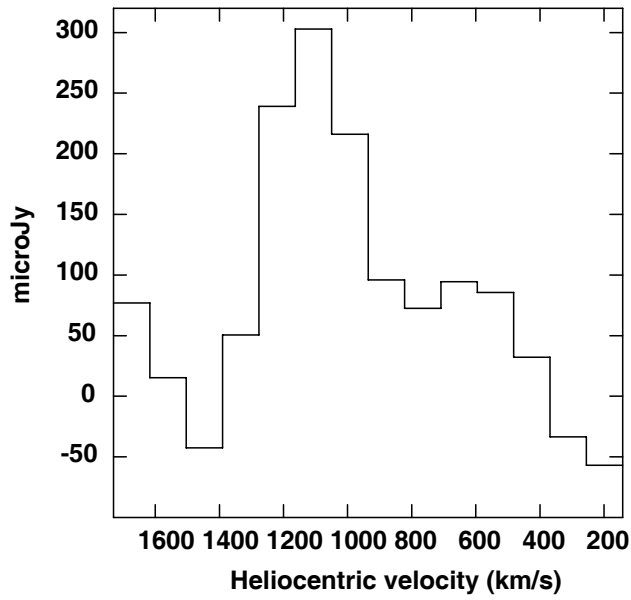
(b) 8.3 GHz DnC configuration continuum image of NGC 1808

Figure 6.2: 8.3 GHz continuum emission from NGC 1808 imaged with the VLA in the (a) CnB configuration and (b) DnC configuration. The synthesized beams are, respectively, $3.6'' \times 2.5''$ at a P.A. of -6° and $11.3'' \times 8.2''$ at a P.A. of -8° . The rms noise in the two images are $35 \mu\text{Jy/beam}$ and $33 \mu\text{Jy/beam}$ and the contour levels plotted are $(10, 20, 40, 60, 100, 120, 140, 160, 180, 220, 260, 300, 340, 380, 420, 460, 500, 540) \times \text{rms}$ and $(10, 15, 18, 40, 80, 160, 320, 640, 1280, 1600) \times \text{rms}$ respectively.

other regions. However, the main difference between the hotspot and the nucleus is that the star formation in the hotspot is much younger than in the nucleus. For a given stellar mass, younger star forming sites are expected to have a larger number of dense compact and ultracompact HII regions compared to older star forming sites. Since a larger mass of low density gas is required to produce a detectable $\text{H}92\alpha$ line compared to higher density gas, we suggest that the relative youth of the starburst in the hotspot is responsible for the fact that it is the only detected (and hence the strongest) source of 8.3 GHz recombination line emission. However, the reason why other Bry knots of similar derived ages as the hotspot are not detected in RRL emission. Models of the ionized gas in the hotspot and also the nucleus and surrounding regions are discussed in detail below.

6.2.3.1 The hotspot in NGC 1808

We model the thermal gas in the hotspot using the measured continuum and line strengths at 8.3 GHz along with the 1.4 GHz continuum emission (Saikia et al., 1990). These data are measured over a region corresponding to a single synthesized beam area of size $3.1''$ or 165 pc. Hence we model the line emitting gas both as an uniform slab (Model II) and a collection of HII regions (Model III), since a single spherical HII region is unlikely. Apart from the constraints from the observed line and continuum emissions, an additional constraint based on the higher resolution continuum observations is also imposed. Saikia et al. (1990) imaged the radio continuum from this galaxy at 15 GHz using the VLA with a beam of $0.7'' \times 0.4''$ and



(a) H92 α spectrum towards hotspot of NGC 1808

Figure 6.3: The Hanning smoothed H92 α spectrum against the peak of the continuum hotspot in NGC 1808 for the CnB configuration data. The synthesized beam is $3.5'' \times 2.5''$ and the 1σ noise in the channel image is $97 \mu\text{Jy}/\text{beam}$. The line is seen to extent between 900 and 1300 km s^{-1} . The shoulder of emission towards the lower velocity side is unlikely to be real.

detected emission only from the nucleus. The 5σ upper limit to the 15 GHz emission from the region around the hotspot is 1.0 mJy/beam, implying an equivalent upper limit on the total intensity of the continuum radiation. For each combination of input parameters in a given model, the 15 GHz free-free intensity can be calculated. Since the area filling factor of the thermal gas inside the $3.1''$ beam is found to be much less than unity for all model solutions, the exact distribution of this gas inside this region is unknown. Conservatively, we assume that the thermal gas is spread homogeneously over the entire region, i.e., the flux density of the free-free emission in every $0.7'' \times 0.4''$ area inside the $3.1''$ beam is assumed to be equal. We also calculate the predicted intensity of the observed non-thermal radiation, (after correcting for absorption by the thermal gas appropriate to the relative geometry assumed) $S_{(\text{nth obs})}$. The resulting total radiation intensity is constrained to be less than 1.0 mJy. That is, in Model II,

$$\frac{(S_{ff} + S_{(\text{nth obs})})_{\nu=15 \text{ GHz}}}{(L^2/D^2)} \times \left(\frac{0.7'' \times 0.4''}{(\text{radian/arcsec})^2} \right) \times \left(\frac{0.7'' \times 0.4''}{3.1'' \times 3.1''} \right) < 1.0 \text{ mJy} \quad (6.1)$$

and a similar expression holds for the filling factor corrected intensity in Model III, wherein, S_{ff} is replaced by S_{ff}/f_1 , where L is replaced by B and f_1 is defined in section 2.3.1. S_{ff} is the free-free flux density, in mJy, D is the distance to the galaxy, L is the transverse length of the uniform slab, B is the size of the volume containing the collection of HII regions, and $f_1 = (1 - e^{-N_{\text{los}}})$ where N_{los} is the average number of HII regions along a line of sight. The derived solutions for the two models are similar. The allowed range of electron density is in the range $1000\text{-}10000 \text{ cm}^{-3}$ and the effective size ($\sim \text{volume}^{1/3}$) is in the range 4-11 pc. The ionization rate is $(4\text{-}8) \times 10^{52} \text{ s}^{-1}$. The free-free flux density at 8.3 GHz is 1-2.5 mJy (15-35 % of the total continuum) and at 15 GHz, is 2.0-3.7 mJy. The predicted frequency dependence of the

line and continuum emission as a function of frequency for typical solutions is shown in figure 6.4. Using the 5σ upper limit of $1.0 \text{ mJy}/(0.7'' \times 0.4'' \text{ beam})$ for the total 15 GHz continuum intensity, the lateral angular extent of the free-free emitting thermal gas can be estimated to be larger than 40-54 pc ($0.75''$ - $1.0''$). Since more than half of the total 15 GHz continuum emission is non-thermal, the lower limit to the size of the thermal gas is even higher. Hence, if the thermal gas is assumed to be spatially contiguous in the lateral direction, its size is determined to be 4-11 pc. However, by the above argument, it must be extended over a region much larger than 40 pc and must hence be clumped. Therefore we conclude that the ionizing source for the RRL emitting gas must be in the form of isolated star clusters, each contributing no more than 2×10^{52} ionizing photons s^{-1} .

Using the derived value of $N_{\text{Ly}\alpha} = (4-8) \times 10^{52} \text{ s}^{-1}$, the $\text{Br}\gamma$ flux is computed to be $(3.5-7) \times 10^{-17} \text{ W m}^{-2}$. Krabbe, Sternberg & Genzel (1994) measured the $\text{Br}\gamma$ fluxes in a $2.6''$ aperture around each thermal knot and the extinction corrected $\text{Br}\gamma$ flux from the hotspot region is $2.6 \times 10^{-17} \text{ W m}^{-2}$. The estimate based on the data of Kotilainen et al. (1996) is $1.6 \times 10^{-17} \text{ W m}^{-2}$. Hence the extinction derived in these studies is probably an underestimate. It is of course possible that the $\text{Br}\gamma$ emission and the RRL emission arise from distinct components of thermal gas.

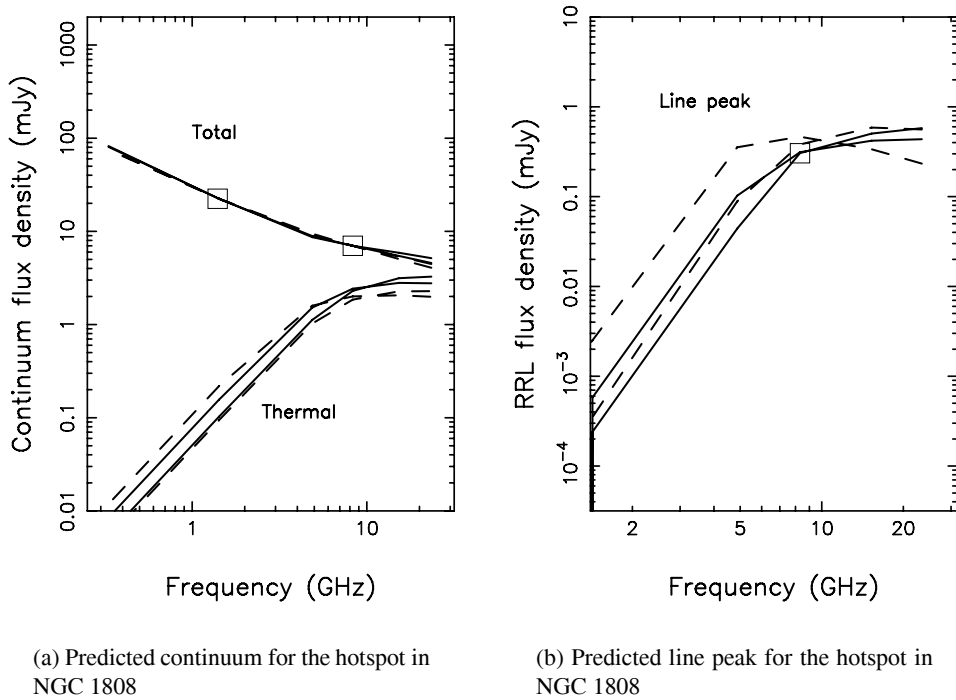


Figure 6.4: Predicted (a) free-free and total continuum and (b) line flux densities for the hotspot in NGC 1808 as a function of frequency. Typical solutions from Model III, a collection of HII regions are plotted as solid lines. The upper curve is for $n_e = 5000 \text{ cm}^{-3}$, $N=20$, $l=2.5 \text{ pc}$, $B=5 \text{ pc}$, $T_e=5000 \text{ K}$ and the lower curve is for $n_e = 10000 \text{ cm}^{-3}$, $N=15$, $l=1.8 \text{ pc}$, $B=200 \text{ pc}$, $T_e=5000 \text{ K}$. The dashed lines correspond to a uniform slab model where the upper curve is for $n_e = 1000 \text{ cm}^{-3}$, $l=33 \text{ pc}$, $b_{ff}=0.003$, $T_e=5000 \text{ K}$ and the lower curve is for $n_e = 5000 \text{ cm}^{-3}$, $l=3.6 \text{ pc}$, $b_{ff}=0.001$, $T_e=5000 \text{ K}$. The measured values are marked by open squares.

6.2.3.2 Nucleus and surrounding star forming sites in NGC 1808

The thermal component of the gas in the $3.1''$ region of the nucleus is modelled as a collection of HII regions. A fraction f_{th} of the observed 8.3 GHz continuum emission S_c is assumed to be due to free-free emission from the thermal gas, where f_{th} is a free parameter in the model. The model solutions are constrained to produce a free-free flux density at 8.3 GHz equal to $f_{\text{th}} \times S_c$ and a H92 α line strength less than the measured 3σ upper limit. By an argument similar to that in the previous section, the filling factor corrected prediction for the observed continuum flux density at 15 GHz for a $0.7'' \times 0.4''$ beam is also constrained to be less than the observed value of 9 mJy. Valid solutions are obtained only for a value of $f_{\text{th}} < 25\%$, consistent with estimates by Krabbe, Sternberg & Genzel (1994) and Kotilainen et al. (1996). The derived densities range is not well constrained and is in the range $50\text{--}10000\text{ cm}^{-3}$. This calculation can be repeated in the case of the Bry/radio knots surrounding the nucleus, which are observed in high resolution images. The average continuum emission at 8.3 GHz measured at the locations of these knots is 6 mJy/beam, which is used in the models as a constraint on the free-free emission. The maximum allowed thermal fraction is derived to be 10 % and the allowed range in gas density is the same as for the nucleus.

6.3 II Zw 40

6.3.1 Introduction

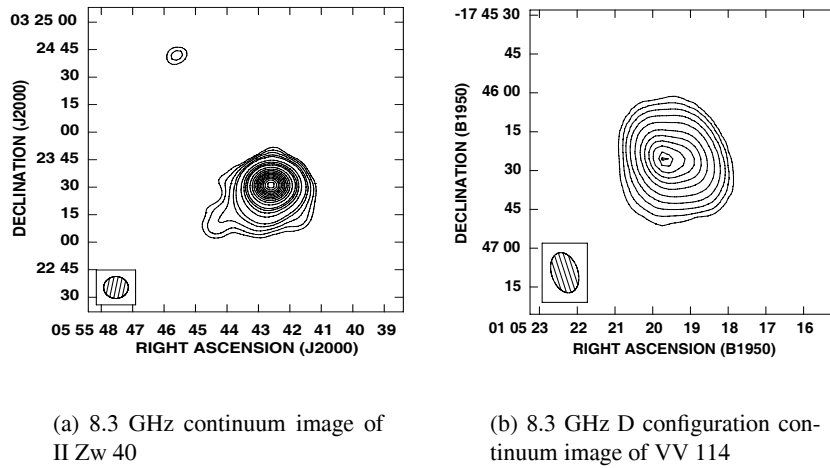


Figure 6.5: **(a).** 8.3 GHz continuum image of II Zw 40 using the VLA in the D configuration. The synthesized beam is $11.9'' \times 11.7''$ at a P.A. of -11° and the rms in the image is $20\text{ }\mu\text{Jy/beam}$. The contour levels are (5, 7, 10, 15, 20, 40, 60, 80, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650) times the rms. **(b).** 8.3 GHz continuum image of VV 114 in the D configuration. The contour levels are (10, 20, 40, 80, 160, 320, 500, 700, 900, 1100, 1170) $\times$ rms in the image, which is $23\text{ }\mu\text{Jy/beam}$. The synthesized beam is $16.0'' \times 10.0''$ at a P.A. of 18° .

II Zw 40 ($D=10.5\text{ Mpc}$) is a blue irregular dwarf starburst galaxy and was one of the first Blue Compact Dwarfs to be identified and studied (Sargent & Searle, 1970). Its optical image is dominated by a central core consisting of a star cluster and fainter tidal tails (Sargent, 1970; Baldwin, Spinrad & Terlevich, 1982). The optical spectrum is dominated by strong narrow

emission lines (Sargent, 1970; Walsh & Roy, 1993) and broader Wolf-Rayet features (Kunth & Sargent, 1981). Strong NIR lines have also been seen. The radio continuum emission is predominantly thermal in origin (Wynn-Williams & Becklin, 1986; Sramek & Weedman, 1986; Klein, Weiland & Brinks, 1991; Deef et al., 1993; Beck et al., 2002). Though these observations show that II Zw 40 is undergoing a strong starburst, Sage et al. (1992) did not detect any significant quantity of molecular gas in CO emission. Thus, this galaxy resembles NGC 5253 to a remarkable extent. Recently, Beck et al. (2002) imaged the 2 cm radio continuum from the core of II Zw 40 at high resolution ($\sim 0.13''$) using the VLA and discovered four unresolved objects. They identify the continuum emission as due to free-free radiation and hence suggest that these objects are similar to young ‘supernebulae’ discovered in NGC 5253 (Turner, Beck, & Ho, 2000), or ‘ultra dense HII regions’ discovered in He 2-10 (Kobulnicky & Johnson, 1999). Each of these four continuum sources are powered by star clusters of ~ 600 O stars each. The rms gas densities are $\sim 3 \times 10^4 \text{ cm}^{-3}$ and diameters are ~ 1 pc. The total ionization required for these four nebulae is $\sim 2.4 \times 10^{52} \text{ s}^{-1}$. They also image the $12 \mu\text{m}$ emission from the galaxy at lower resolution and show that the inner core consisting primarily of these radio ‘supernebulae’, is responsible for almost all of the FIR luminosity as well.

6.3.2 Observations and Results

II Zw 40 was observed at 8.3 GHz using the VLA in the D configuration in two runs. The observational parameters are listed in table 6.1. The continuum image of the combined dataset is shown in figure 6.5a. The prominent southeast extension in the image was first detected at a smaller scale by Klein, Weiland & Brinks (1991) and identified with the spatially coincident optical plume. This extension also coincides with the plume observed in the K band by Vanzi et al. (1996). The less prominent extension observed by Klein, Weiland & Brinks (1991) towards the SW has no counterpart in our 8.3 GHz image and is also not detected in an image made at higher resolution. The H92 α line is not detected in the line cube. The 3σ upper limit on the line flux is $6 \times 10^{-24} \text{ W m}^{-2}$.

6.3.3 Modelling the ionized gas

Beck et al. (2002) detected four radio continuum objects with thermal spectra. All four objects are spatially unresolved with a $0.13''$ beam and the 15 GHz peak flux densities are ~ 0.6 mJy/beam. We therefore model an individual HII region as a sphere of uniform density constrained to produce a 15 GHz continuum free-free emission of 0.6 mJy. Solutions are obtained for $n_e \geq 5 \times 10^3 \text{ cm}^{-3}$ with the size of the HII region decreasing with increasing density. We calculate the expected 8.3 GHz H92 α line flux for the various model solutions. The total (for all four objects) H92 α line strength is 60-70 % of the observed 3σ upper limit for densities between 5000 and 10000 cm^{-3} , is about 40 % for $n_e \sim 50000 \text{ cm}^{-3}$ and decreases further for higher densities.

6.4 NGC 7552

6.4.1 Introduction

NGC 7552 ($D=20$ Mpc) is an almost face-on barred spiral starburst galaxy with two pronounced spiral arms, emerging from the ends of the bar. Two star forming rings of radii 1.9 kpc and 3.4 kpc have been detected in the optical and infrared (Feinstein et al., 1990; Schinnerer et al., 1997). Forbes, Kotilainen & Moorwood (1994) imaged the 8.3 GHz continuum emission and discovered a third ring of size 1 kpc, consisting of a number of hotspots. The three rings, in increasing order of radius, correspond to co-rotation, Inner Lindblad Resonance and Outer Lindblad Resonance of the bar. The inner ring is easily detected in NIR and optical colour images (Forbes et al., 1994), in MIR broadband images (Schinnerer et al., 1997) and also in Br γ images. A number of Br γ knots lie along the ring and show weak correlation with the radio knots. The nucleus is inactive, with no AGN or starburst features and does not emit radio or infrared emission.

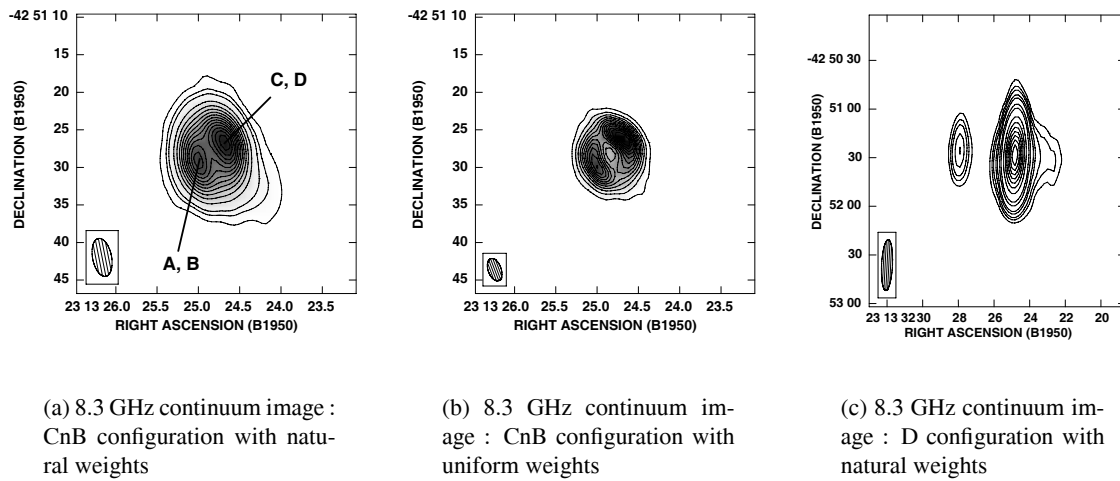


Figure 6.6: 8.3 GHz continuum images of NGC 7552 using data from (a) CnB configuration with natural weighting. The rms in the image is $33 \mu\text{Jy}/\text{beam}$ and the contour levels are (10, 20, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330, 360, 390) $\times$ rms. The synthesized beam is $5.1'' \times 2.5'' @ 11^\circ$. (b) CnB configuration with uniform weighting. The rms in the image is $58 \mu\text{Jy}/\text{beam}$ and the contour levels are (10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130) $\times$ rms. The synthesized beam is $3.1'' \times 1.7'' @ 20^\circ$. (c) D configuration with natural weighting. The rms in the image is $45 \mu\text{Jy}/\text{beam}$ and the contour levels are (10, 15, 20, 30, 40, 70, 100, 200, 300, 400, 500, 600, 700, 800) $\times$ rms. The synthesized beam is $31.4'' \times 6.7'' - 3^\circ$.

6.4.2 Observations and results

This galaxy was observed at 8.3 GHz using the VLA in the CnB and D configurations. The continuum images are shown in figure 6.6. The ring is unresolved in the D array image. Also, since we observed this southern source with the VLA in the D configuration, the beam is quite elongated in the N-S direction. The rms is higher than in the CnB array data since about half of this data were lost due to hardware problems during observations. The CnB dataset has a synthesized beam of $5.1'' \times 2.5''$ and hence resolves the ring of emission but does not resolve the

individual radio knots seen by Forbes, Kotilainen & Moorwood (1994). Instead, the sources A and B are merged into a single source and so are sources C and D. The H92 α line is not detected in either of two datasets. The observational and image parameters are summarised in table 6.1. We do not use the D array data while determining the upper limit to the line emission, due to its higher noise.

6.4.3 Modelling the ionized gas

Since we do not detect any line emission, we model the properties of the thermal gas as in the previous sections. The model solutions are constrained to produce free-free emission of $f_{\text{th}} \times S_c$ and a H92 α line strength less than the observed upper limit. Based on the bolometric luminosity derived by Schinnerer et al. (1997), the FIR luminosity is assumed to be about $2 \times 10^{10} L_{\odot}$ and the corresponding IRE is constrained to be >1 . The gas parameters are not well constrained and the allowed range is similar for both A,B and C,D complexes. The thermal fraction is derived to be less than 70 % and the lower limit to the density is 50 cm^{-3} . The upper limit to the density is 1000 cm^{-3} for $f_{\text{th}} \sim 60 \%$ and increases for lower values of f_{th} .

6.5 VV 114

6.5.1 Introduction

VV 114 (= Arp 236 = IC 1623) is a nearby ($D=77 \text{ Mpc}$) ULIG whose FIR luminosity is $4.2 \times 10^{11} L_{\odot}$ and belongs to the IRAS Bright Galaxy Sample. This galaxy is undergoing a merger between the two nuclei VV 114 E and VV 114 W, separated by $15''$ (5.6 kpc). The two merging galaxies show a remarkable contrast in their continuum spectra (Knop et al., 1994; Doyon et al., 1995; Goldader et al., 2002). VV 114 W is visible from the UV (Goldader et al., 2002) down to the IR and has little dust extinction. VV 114 E, however, is almost invisible in the UV and optical and is only observed in the IR, sub-mm and radio (Condon et al., 1991), due to much higher dust extinction. IR imaging shows that star formation is spread throughout the system and the NIR continuum emission is extended (Knop et al., 1994). Doyon et al. (1995) imaged VV 114 in the NIR with a resolution of $0.7''$ and detected two distinct bright IR sources in VV 114 E. They also estimated that about half the total IRAS luminosity originates in the eastern source. Yun, Scoville & Knop (1994) imaged the CO emission and detected a total molecular gas mass of $5 \times 10^{10} M_{\odot}$ in a 6 kpc sized region between the two nuclei. From the morphology and the extent of non-circular kinematics, they deduce that the merger of gas is at a more advanced stage than that of stars and that the reservoir of gas detected by them would form a much stronger starburst in the future. The sub-mm imaging carried out by Frayer et al. (1999) shows that the emission lies along the CO bar and consists of a strong peak near VV 114 E. Scoville et al. (2000) imaged the NIR emission using the HST and detected a number of luminous star formation regions in VV 114 W and also found star clusters in the overlap region. They detected an unresolved source in VV 114 E which is probably an obscured AGN. Goldader et al. (2002) estimated that the AGN is responsible for about half the IR luminosity of VV 114 E and the remaining arises due to reddened starlight.

6.5.2 Observations and results

VV 114 was observed at 8.3 GHz using the VLA in the D configuration. The observational parameters are listed in table 6.1. The E and W components are barely resolved in the continuum image shown in figure 6.5.. No line emission was detected towards this galaxy and the 3σ upper limit to the line emission, assuming a line width of about 110 km s^{-1} , is $4.0 \times 10^{-23} \text{ W m}^{-2}$ (corresponding to 1.2 mJy/beam).

6.5.3 Modelling the ionized gas

The thermal component of VV 114 E was modelled, constrained by the upper limit to the $\text{H}92\alpha$ line emission and a free-free emission of $f_{\text{th}} \times S_c$ where S_c is 27.2 mJy at 8.3 GHz . The IRE was constrained to be greater than unity by assuming that the FIR luminosity of VV 114 E is $1 \times 10^{11} L_{\odot}$. Consistent solutions were obtained only for a thermal fraction $\leq 20 \%$, i.e., $S_c \leq 5.4 \text{ mJy}$. If this thermal gas is optically thin at 8.3 GHz , then the ionization rate is $< 3 \times 10^{54} \text{ s}^{-1}$.

6.6 Discussion

In the previous chapter, the observed recombination line emissions from selected galaxies were modelled in order to derive the properties of the ionized gas in these objects. We have also, as described partly in this chapter, attempted to detect the $\text{H}92\alpha$ line emission at 8.3 GHz from a sample of seven galaxies, with a rather low success rate of $\sim 40 \%$. Therefore, in order to understand this detection rate, we investigate the following issues in this section: (1) Can the available data be used to predict whether a given galaxy will be detected in RRL emission ? Why are some galaxies detected and some others not ? and (2) If a galaxy is indeed detected in recombination line emission, what are the implications for the star formation properties of that galaxy ?

6.6.1 Correlations between the $\text{H}92\alpha$ emission and SFR tracers

A total of twenty-three galaxies have been observed at 8.3 GHz to search for line emission and the $\text{H}92\alpha$ line has been detected in twelve of them, implying a detection rate of $\sim 50 \%$. The galaxies with observed line emission are NGC 253 (Anantharamaiah & Goss, 1990), NGC 3628, IC 694, NGC 1365 (Anantharamaiah et al., 1993), Arp 220, M 83, NGC 2146 (Zhao et al., 1996), NGC 3690 (Zhao et al., 1997), NGC 660 (Phookun, Anantharamaiah, & Goss, 1998), NGC 1808, NGC 5253 and He 2-10 (this work). The $\text{H}92\alpha$ line has not been detected in NGC 262, NGC 1068, NGC 3079 (Anantharamaiah et al., 1993), NGC 6240 (Zhao et al., 1996), NGC 520, NGC 1614, NGC 6946 (Phookun, Anantharamaiah, & Goss, 1998), NGC 4038/9, NGC 7552, VV 114 and II Zw 40 (this work). For a smaller sample of thirteen starburst galaxies, Zhao et al. (1996) found that the $\text{H}92\alpha$ line luminosity is correlated with the $\text{Br}\gamma$ line luminosity, though with evidence for significant non-LTE enhancement of the RRL line emission. They also found a stronger correlation between the $\text{H}92\alpha$ luminosity and the luminosity of the HCN/HCO^+ line luminosity. Since these molecular lines arise in dense gas ($n_e > 10^4 \text{ cm}^{-3}$), the authors suggested that the $\text{H}92\alpha$ emitting ionized gas is related to dense molecular cores in starburst galaxies.

A number of global parameters of starburst galaxies like the CO luminosity, luminosity of dense gas tracers (like HCN, CS) and radio luminosity are well correlated with the FIR luminosity. The latter quantity is believed to be one of the basic attributes of the starburst since it is directly and causally connected to the total star formation rate. Hence, in this section, we study the relationship between the H92 α emission, the total FIR emission and the total 1.4 GHz continuum emission for the entire sample of 23 galaxies. The 1.4 GHz continuum emission is determined using the archived NVSS images of the galaxies, which have been obtained using the VLA in the D configuration (Condon et al., 1998). The FIR emission corresponds to the total IR flux in the IRAS bands. These quantities are plotted in figure 6.7 in terms of total flux and in figure 6.8 in terms of luminosity.

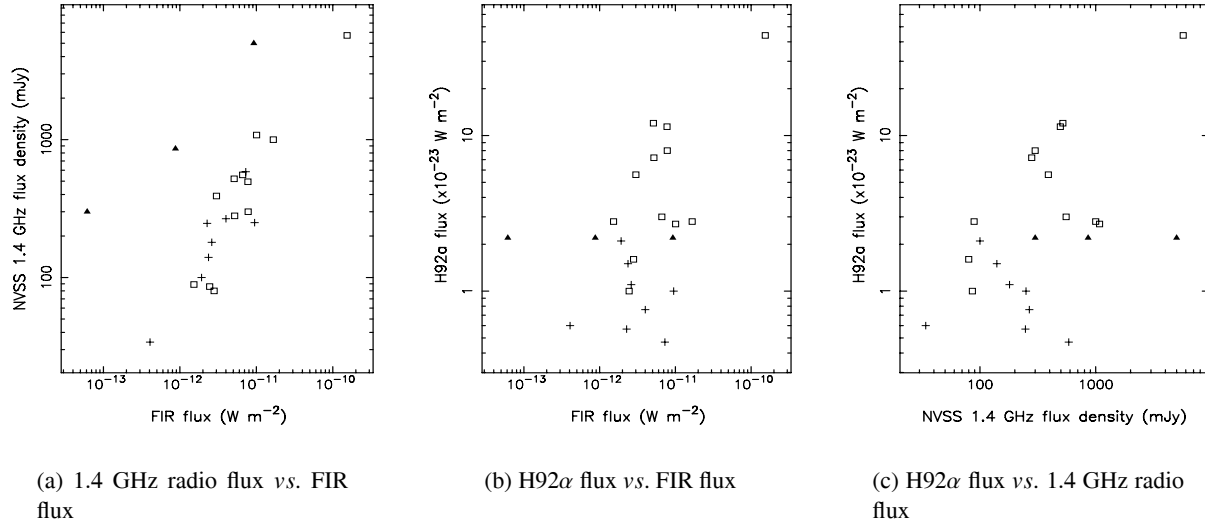


Figure 6.7: Flux-flux plots between the H92 α , 1.4 GHz radio (NVSS) and FIR fluxes for the sample of 23 galaxies. Galaxies with H92 α detections are marked as open squares. The plus symbols and solid triangles denote galaxies with upper limits to the H92 α emission. The solid triangles indicate the three galaxies which do not lie on the radio-FIR correlation.

The 1.4 GHz radio and FIR fluxes as well as luminosities correlate strongly with each other, as expected. This, of course, is the well-known radio-FIR correlation for star forming galaxies. However, three galaxies, NGC 262, NGC 1068 and NGC 3079, denoted by the solid triangle symbol, do not follow the radio-FIR correlation. Since they have a larger ratio of radio to FIR luminosities compared to the rest of the sample, this discrepancy is probably due to radio emission from a central AGN. Hence these three galaxies, none of which have been detected in RRL emission, are denoted by separate symbols. It is not clear whether the RRL line flux is correlated with the FIR and the radio fluxes. However, it can be seen even visually from figure 6.8 that the H92 α luminosity is well correlated with the FIR luminosity as well as with the 1.4 GHz radio luminosity. Since the radio and FIR emissions are known to be tightly correlated for starburst galaxies (Condon, 1992), it is to be expected that if the H92 α luminosity of these galaxies is correlated with the FIR luminosity, then it will also be correlated with the radio luminosity and vice versa.

It is often claimed that if a class of objects with a large range of distances or redshifts are detected over a small range of apparent brightness or flux, then an artificial correlation will

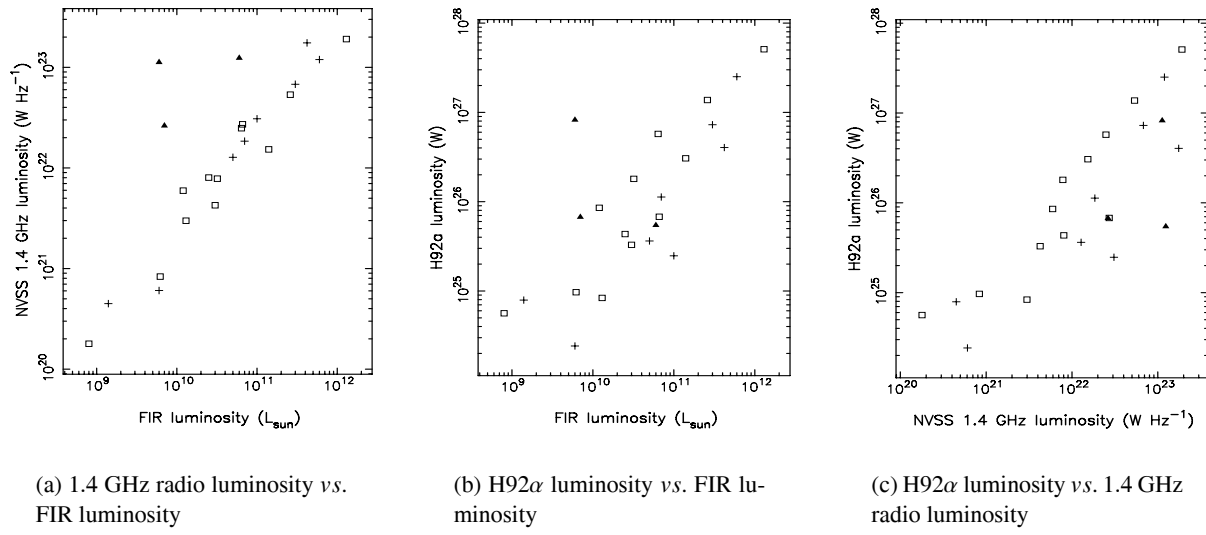


Figure 6.8: Luminosity-luminosity plots between the H92 α , 1.4 GHz radio (NVSS) and FIR luminosities for the sample of 23 galaxies. Galaxies with H92 α detections are marked as open squares. The plus symbols and solid triangles denote galaxies with upper limits to the H92 α emission. The solid triangles indicate the three galaxies which do not lie on the radio-FIR correlation.

appear when absolute luminosities are considered, even when there is no correlation between the corresponding flux densities. However, Feigelson & Berg (1983) convincingly argue the converse, i.e., in order to search for a true correlation, it is the luminosities which should be plotted and not the fluxes : ‘... a class of objects will not be detected in narrow flux ranges at two frequencies *unless* an intrinsic relationship is present; flux upper limits in one band will be obtained for the more distant objects if no relationship exists.’ They show that if the observed upper limits (or censored data points) are also taken into account, then the luminosities can be used to determine whether an intrinsic correlation exists. Flux-flux correlations are not adequate for this purpose except in special circumstances.

Table 6.3: Generalised Kendall’s τ correlation test for luminosities

Correlation	Probability of correlation (%) for	
	23 galaxies	20 galaxies ^a
Radio vs. FIR	99.2	99.99
Radio vs. H92 α	98.2	99.7
FIR vs. H92 α	99.7	99.6

^aThis sample of 20 galaxies excludes NGC 262, NGC 1068 and NGC 3079 which do not lie on the radio-FIR correlation

Since the possible correlation between the H92 α and radio or FIR luminosities is to be tested, a bivariate statistical method will be used. The sample of 23 galaxies studied here has not been chosen in a uniform fashion and the distribution of the parent population is not known. Hence, a non-parametric method is needed in order to test for a correlation. We use the Generalized Kendall’s τ correlation test for this purpose (Isobe, Feigelson & Nelson, 1986). Zhao et al. (1996) also employed this test in order to determine the correlation between the H92 α luminosity and the Br γ and the HCN/HCO⁺ line luminosities. We used the ASURV

software package (developed for applications of ‘survival analysis’ techniques) for performing this test. The test was performed for the entire sample of 23 galaxies as well as for the sample of 20 galaxies excluding the three which do not lie on the radio-FIR correlation. Kendall’s test yields the probability that the given correlation is indeed real and these values are summarised in table 6.3. As expected, the highest probability is obtained for the radio-FIR correlation. However, the H92 α emission is indeed well correlated with the FIR (and radio) emission and the probability for this correlation to be real is as high as 99.7 % for the FIR-H92 α pair. The FIR luminosity is proportional to the Star Formation Rate (SFR). Hence we conclude that the stronger the SFR, stronger is the H92 α emission.

However, figures 6.7 and 6.8 show that L_{FIR} (and hence SFR) is not the only determining factor for the H92 α emission. If L_{FIR} were the only factor, then the lack of detection of the H92 α emission from the remaining 11 galaxies cannot be explained. Hence additional factors must exist, which are also responsible in determining the total H92 α luminosity. It must be noted that the analysis described in this section has been carried out only for the H92 α luminosity and not, for example, the sum of RRL emission over a wide range of frequencies. Hence, peculiarities in the production and detection of the H92 α line might influence the detection rate. This issue is investigated in the next section.

6.6.2 Detectability of line emission from nearby galaxies

Detection of RRLs from nearby starbursts requires the presence of gas with large emission measures since most of the observed line radiation is due to internal emission. RRL detection experiments are not unbiased surveys. Due to non-LTE and also continuum optical depth effects, a particular RRL chosen for observation could well be affected by a certain bias, or a certain filter, in the parameter space of the gas properties. That is, for a given combination of observational parameters and typical galaxy properties, a particular RRL might not be detectable from gas at any density and mass. The spatial resolution of the observation and the typical size of the line emitting gas will affect the detectability of these lines. Note that this selection effect will also include the effects of sensitivity limitations of observations currently possible. In this section, we investigate whether there exists an a priori bias in the gas density-RRL frequency plane, i.e., whether the selection of a particular recombination line biases the observations towards a particular range in gas density. Figure 6.9 illustrates the behaviour of the RRL emission and can be used to illustrate the nature of this selection effect. Note that there are two distinct issues to be addressed. First, in the case of multi-density ionized gas, if the mass of gas at each density (or in every uniform density bin) is equal, then from which range of densities will most of the observed emission of a given line arise ? This question was dealt with in chapter 2 and it was shown that due to non-LTE effects, lower the frequency of the recombination line, lower is this preferred density range. Second, even if there is no gas present in the preferred density range of a certain line, then for typical observational and source properties, will that line be detectable from gas at other densities instead ? We attempt to address the second question in this section.

In this calculation, an ionizing photon rate $N_{\text{Ly}\alpha}$ of $2 \times 10^{53} \text{ s}^{-1}$ is assumed as typical of a starburst galaxy. Using this value, for a given gas density, the size of the spherical HII region can be calculated, and further, for an assumed distance D to the galaxy, the angular diameter θ of the HII region can also be computed. These values are plotted in figure 6.9. The 1.4 GHz H166 α flux density as a function of the angular diameter θ is also shown in the figure. Similarly, the 8.3

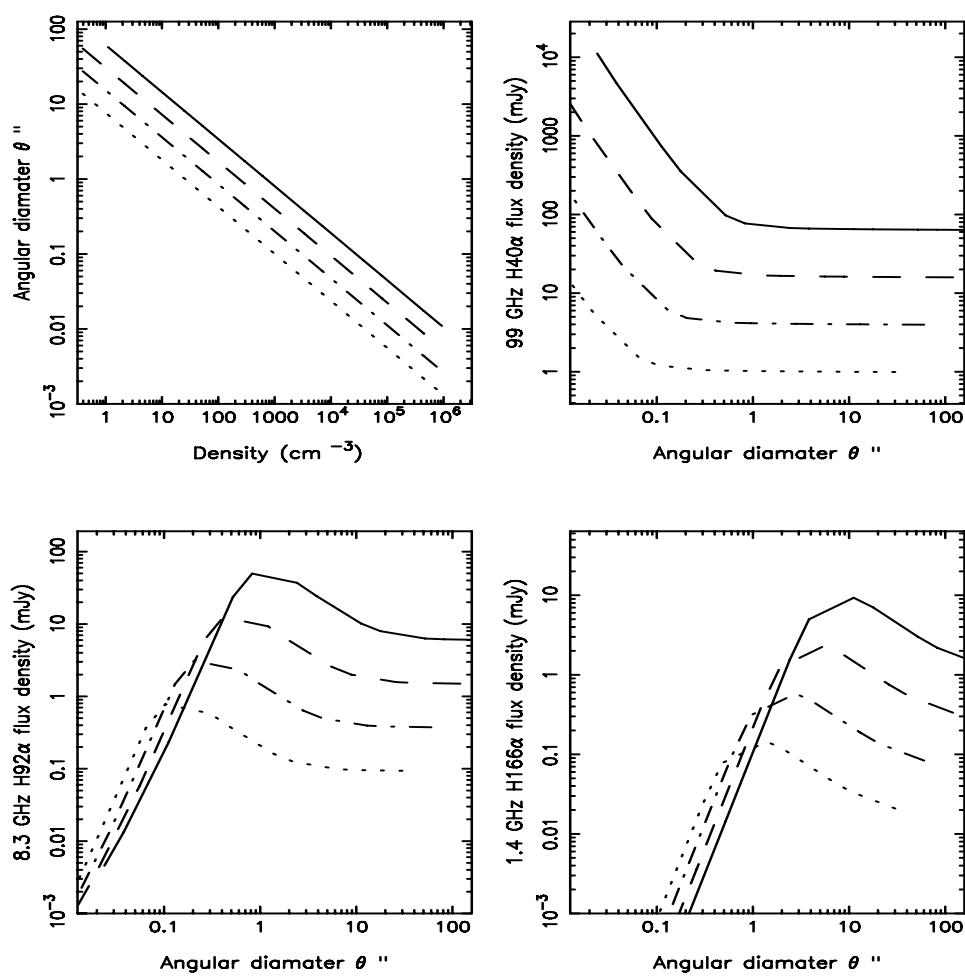


Figure 6.9: The first sub-plot indicates the density dependence of angular diameter θ for a spherical extragalactic HII region with $N_{\text{Ly}\alpha} = 2 \times 10^{53} \text{ s}^{-1}$. The solid, dashed, dash-dotted and dotted curves are for a distance D to the galaxy of 2.5, 5, 10 and 20 Mpc respectively. The H40 α , H92 α and H166 α line flux densities as a function of θ are shown in the other three sub-plots for the four values of D .

GHz H92 α flux density and the 99 GHz H40 α flux density are also plotted. In all three cases, only the internal emission component of the line is calculated, i.e., the externally stimulated emission component is assumed to be zero. The H92 α line emission (and also the H166 α line) exhibits a maximum as a function of θ , which arises because θ is a monotonic function of density. This value of θ is 0.3''-3'', which corresponds to a density of $\sim 10^3$ - 10^4 cm^{-3} . It should be noted that this range of values of θ is marginally less than the typical resolution of our observations. In the case of the 1.4 GHz line emission, $\theta \sim 1''$ -10'' and the density is 10 - 10^3 cm^{-3} , whereas for the 99 GHz line, $\theta < 0.3''$ and the gas density is $> 10^4 \text{ cm}^{-3}$.

Consider again, the behaviour of the H92 α line emission as shown in figure 6.9. If this line emission is to arise predominantly in gas at densities much lower than the above mentioned range of 10^3 - 10^4 cm^{-3} , then the size of the HII region must be larger (for the same value of $N_{\text{Ly}\alpha}$) and hence the angular diameter θ will increase. However, this will lead to less line flux per synthesized beam. From the H92 α flux density values plotted in the figure for typical distances D , it can be inferred that the line emission from gas at much lower densities will not be observed. If, therefore, the value of θ is to remain the same, then the value of $N_{\text{Ly}\alpha}$ would have to be less, again leading to much weaker lines. If on the other hand, the H92 α line

emission is to arise predominantly in gas at densities much higher than the derived range of 10^3 - 10^4 cm^{-3} , then for the assumed value of N_{Lyc} , the line flux is weaker. If the value of θ is kept constant, then a much larger value of N_{Lyc} is required which occurs in very few galaxies. A similar analysis can also be performed for the line emission at 1.4 GHz and 99 GHz. By comparing the plots for the various frequencies, it can also be concluded that if RRL emission is to be detected from low density gas ($\lesssim 10^2 \text{ cm}^{-3}$), then either (1) the galaxy should be very nearby, $< \text{few Mpc}$, or (2) RRLs should be observed at frequencies less than $\sim 1 \text{ GHz}$.

Hence we infer that for typical values of N_{Lyc} and synthesized beam sizes, a given line is preferentially detected from a particular range in densities. Therefore it is possible that if the $\text{H}92\alpha$ line is not detected from a galaxy, then there is not enough ionized gas at the suitable density range of 10^3 - 10^4 cm^{-3} and most of the ionized gas are at very different densities.

6.6.2.1 Gas density of proto-SSC molecular clouds

RRL models for the $\text{H}92\alpha$ line yield gas densities of a few 10^3 cm^{-3} to 10^4 cm^{-3} and the preceding section suggests that this is possibly an observational selection effect. However this explanation cannot account for all the observed cases. In the case of NGC 5253 and He 2-10, the rms gas density inferred from radio continuum observations (Turner, Beck, & Ho, 2000; Kobulnicky & Johnson, 1999) are comparable to that derived from RRL modelling and is $\sim 10^4 \text{ cm}^{-3}$. Therefore, almost all of the ionized gas in these two galaxies is indeed at this density. Also, in the case of NGC 253, $\text{H}92\alpha$ and $\text{H}75\alpha$ line data are available for the radio nucleus and hence the estimated value of density of the gas in the nucleus, which is $\sim 10^4 \text{ cm}^{-3}$, is reliable. Additionally, the compact sources modelled within the central 15 pc region of this galaxy are observed with a resolution of $\sim 4 \text{ pc}$ and hence it is improbable that these regions contain substantial amounts of gas at very different densities. Hence there is some evidence for the existence of compact HII regions in some starburst galaxies which are preferentially at densities of $\sim 10^4 \text{ cm}^{-3}$.

This commonly occurring relatively high density of $\sim 10^4 \text{ cm}^{-3}$ for the compact ionized gas in NGC 253, He 2-10 and NGC 5253 and also in other starburst galaxies (Gilbert et al 2000, Zhao et al 1997, Anantharamaiah et al 2000, TBH00, KJ99) is striking. One model which may be able to explain the high densities is that of Jog & Das (1992, 1996). In their model, a GMC in the centre of a starburst region is shocked by the overpressure of the surrounding molecular inter-cloud medium (ICM). There is evidence for the presence of such a inter-molecular cloud molecular medium in the Galaxy as well as in a few external galaxies (Bally et al., 1987; Stark et al., 1989; Wilson & Scoville, 1990; Downes et al., 1992; Aalto et al., 1994). The outer shell of the GMC is shock-compressed and moves inwards, and at a later stage, due to onset of gravitational instabilities, it fragments into star forming centres. This model can well explain the formation of SSCs of mass $\geq 10^5 M_{\odot}$. An estimate of the density of the shell fragments when star formation begins in the imploding shell is possible. From Jog & Das (1996), the velocity of the shock V_s at the onset of gravitational instabilities can be as high as $\sim 30 \text{ km s}^{-1}$ and the radius of the shock front reaches $\sim 40\%$ of the GMC radius. Adopting a value of the sound speed, C_s , inside the GMC as 4 km s^{-1} , the density of the shocked gas, $n_s = n_o \times V_s^2 / C_s^2$, is increased and the value of the density enhancement n_s / n_o can be greater than 55 (this enhancement can be up to three times larger than this value, for the observed range of values of GMC and ICM properties). In their model, Jog & Das (1992, 1996) assume that the density of the GMC falls radially as r^{-1}

and that the density at the boundary is at least 100 cm^{-3} . Therefore this density enhancement could explain the observed densities of 10^3 - 10^4 cm^{-3} observed in RRLs. It remains to be seen if there is indeed a high pressure reservoir of molecular gas or shocked hot gas at the centres of these galaxies, and if so, whether star formation occurs via this process. It should be noted that CO images of the centres of NGC 5253 and He 2-10 do not show evidence for gas in this region and therefore we would have to appeal to whichever gas reservoir gave rise to the SSCs in the centre to provide the necessary high pressure. However high density ambient medium is not needed in this scenario, since remnant clouds of density $\sim 10^4 \text{ cm}^{-3}$ would still remain in the vicinity of the star cluster and be ionized.

6.6.3 RRL emission as a tracer of the SFR history of a galaxy

In section 6.6.2, it was argued that for typical observational parameters, the choice of a particular recombination line also implies the choice of a preferred range of gas densities the observations are sensitive to. The lack of detection of the $\text{H}92\alpha$ line from almost half the observed galaxies can be explained, possibly, by the relative absence of significant amounts of gas at densities in the range 10^3 - 10^4 cm^{-3} . In reality, a multiplicity of densities would be present in any galaxy. A power law model of such a multi-density ionized gas was constructed in section 2.3.2 and it was shown that, in most cases, the single density approximation is adequate to model the ionized gas properties. However, the availability of RRL data at many frequencies could be used to constrain the amount of gas at different densities, using discrete density components, as in the case of Arp 220 (Anantharamaiah et al., 2000) and NGC 253 (this work).

The star formation rate (SFR) of a starburst galaxy is expected to vary with time and in principle, could exhibit long term (comparable to the duration of the starburst phase) as well as short term variations. Though a single value for the star formation rate (SFR) is often derived for these galaxies, this value is actually a weighted average over the time variation of the SFR. The weighting function depends on the tracer used to measure the SFR and is, in general, not known. In this section, we study the expected time variation of the RRL emission in a simple model for a HII region, though the nature of the weighting function for RRLs will not be discussed.

At any given time, the value of SFR determines the total number of star formed. If the number distribution function for the stars is known, then the distribution function for the ionizing photon rate can be calculated. If the ambient density of the gas from which the stars had formed is assumed to be constant throughout the starburst galaxy and also constant in time, then the distribution function for the size of the initial Strömgren sphere can also be computed. These HII regions will proceed to expand due to thermal overpressure and also due to the energy deposited by stellar winds, leading to a change in the density and size of the HII region as a function of time. Such a model was calculated in section 3.3.2.2 for the case of a single HII region. In the general case, the number of HII regions of a given density and size at any given time will be a convolution of the effect due to the expansion of the HII region and the effect due to the time variation of the SFR. Knowing this time variation of density, size and star formation rate, the time variation of the flux of the various recombination lines can be computed. However, we now study the much simpler case of a single HII region, expanding due to overpressure, where the effect of stellar winds is neglected.

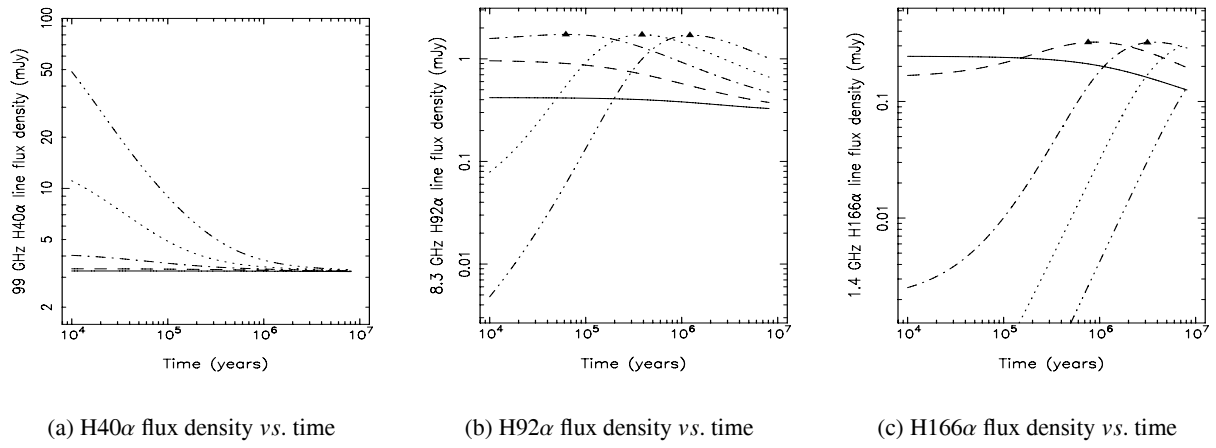


Figure 6.10: The time evolution of the H40 α , H92 α and H166 α line flux densities of a spherical HII region expanding due to thermal pressure. The distance to the galaxy is assumed to be 2.5 Mpc and the value of $N_{\text{Ly}\alpha}$ is 10^{52} s^{-1} . The solid, dashed, dash-dotted, dotted and dot-dot-dashed curves are for an ambient density n_o of 10^2 , 10^3 , 10^4 , 10^5 and 10^6 cm^{-3} . The time when the continuum optical depth equals unity is marked by a solid triangle. If a curve does not contain a solid triangle, then the optical depth either remains higher than unity or remains less than unity throughout the time period shown here.

The radius of the HII region evolves, due to overpressure, as (Spitzer, 1968)

$$R(t) = R_s (1 + at)^{4/7}; \quad a = \frac{7}{4} \frac{c_i}{R_s} \quad (6.2)$$

where c_i is the sound speed in the ionized medium and R_s is the radius of the initial Strömgren sphere, calculated using the ambient density n_o and $N_{\text{Ly}\alpha}$. If $N_{\text{Ly}\alpha}$ is assumed to be constant for the duration of the HII region, then the density and peak optical depth of the spherical HII region evolve as

$$n_i(t) = n_o (1 + at)^{-6/7}; \quad \tau_c(t) = \tau_c(0) (1 + at)^{-8/7} \quad (6.3)$$

and hence decrease with time. Based on these quantities, the RRL flux density can be calculated as a function of time. Shown in figure 6.10 is the time evolution of the flux density of the H40 α , H92 α and the H166 α lines for a galaxy 2.5 Mpc away with an ionization rate of 10^{52} s^{-1} .

For low values of the ambient density n_o , the flux densities of the three lines are almost constant with time. However, for larger values of n_o , which is more typical of starbursts, figure 6.10 shows that the line emission has a maximum as a function of time. This maximum occurs when the continuum optical depth $\tau_c \sim 1$, as marked in the figure. The maximum of the 99 GHz H40 α emission occurs at $t < 10^4$ years. The H92 α line peaks between 10^5 - 10^6 years whereas the 1.4 GHz H166 α line peaks at $t > 10^6$ years. It is known that a particular RRL is sensitive to a specific range in gas densities. In this simple model, the RRL is therefore sensitive to a specific range in the age of the nebula. The exact range of this age of the star formation for a given line depends on the ambient density, the $N_{\text{Ly}\alpha}$ and the SFR history. Note however, that the H40 α flux density at any instant of time never decreases below the H92 α flux density. This can be seen clearly in figure 6.11 where these line flux densities are plotted as a function of frequency for various times. The flux density at a higher frequency is always greater than, or at most equal to, the flux density at a lower frequency, for all times. Based on the figure, it can be inferred that in order to produce a peak in the recombination line flux density as a

function of time, lower the frequency of the recombination line, lower needs to be the ambient density. It can also be seen that for larger values of n_o , the line spectrum evolves from a single power law over a wide range of frequencies to a situation where the power law is modified into a $\sim \nu^0$ behaviour at higher frequencies. This analysis has been carried out in the case of a single HII region and is therefore not a good model for a starburst galaxy. Let us consider two extremes for the SFR history, assuming the ambient density to be constant throughout the galaxy. In the case of an instantaneous star formation (i.e., very short star formation timescale compared to the typical timescales discussed here), the time evolution of the line flux densities will be a convolution of the curves plotted in figure 6.9 with a δ -function and is hence just a scaled version of these plots. Therefore the conclusions arrived at so far, relating the density sensitivity of RRLs to a corresponding age sensitivity would still be applicable. On the other hand, if the star formation rate is constant with time, over a period much longer than 10^6 years, then the convolution of the SFR history with the curves for individual HII regions would yield a constant line flux density as a function of time. In such a case, a particular RRL emission would arise from star forming regions of all ages and hence cannot be used to constrain star formation over recent epochs. However, the flux of different RRLs would not be the same, and would in fact be predictable. Note that the H92 α line would still arise mostly in gas of density between 10^3 - 10^4 cm $^{-3}$. A constant SFR would produce equal amounts of gas at all densities. By modelling widely separated lines, the amount of gas in each density range can be derived and if they are not comparable, then a constant SFR is unlikely. Even if the amount of ionized gas at different densities is the same, that portion of gas whose density lies between 10^3 - 10^4 cm $^{-3}$ would be present in HII regions which are of a definite age (the exact value depending on the ambient density). Hence, to detect a galaxy prominently in the H92 α line emission, there needs to have been sufficiently strong star formation occurring at a particular epoch. This implies, for a constant star formation rate, that the total star formation should therefore be much higher than what is estimated from a single RRL. The actual time evolution of the SFR in typical starbursts is probably in between a purely instantaneous and a purely constant star formation. It might be possible to use the luminosities of a number of RRLs, therefore, to predict the SFR history over the last few 10^6 years.

Hence we suggest that the reason why some galaxies have been detected in H92 α emission whereas some have not is mainly because of differences in the SFR history over the last 10^6 years. Specifically, higher the ratio of the SFR integrated over the last 10^6 years to the SFR integrated over the age of the starburst, stronger the H92 α line emission is expected to be. The detection of the H92 α line from one of the youngest star forming regions (hotspot) in NGC 1808, as opposed to the Br γ brighter nucleus hosting a older starburst supports this interpretation. Also, in NGC 253, the multi-density model of the ionized gas is consistent with the denser ionized gas being present in regions of higher dust extinction, which in turn can be related to a younger star formation age. The ultimate goal of the exercise described in this section is to invert this procedure and obtain the detailed SFR history as a function of time based on RRL data over a wide range of frequencies. Even if that were not possible, from the comparison of the line spectra of two galaxies, i.e., from the ratio of the line spectra, the ratio of the SFR history of the two galaxies can be obtained. Simulations are needed in order to determine the uniqueness and fidelity of such a procedure.

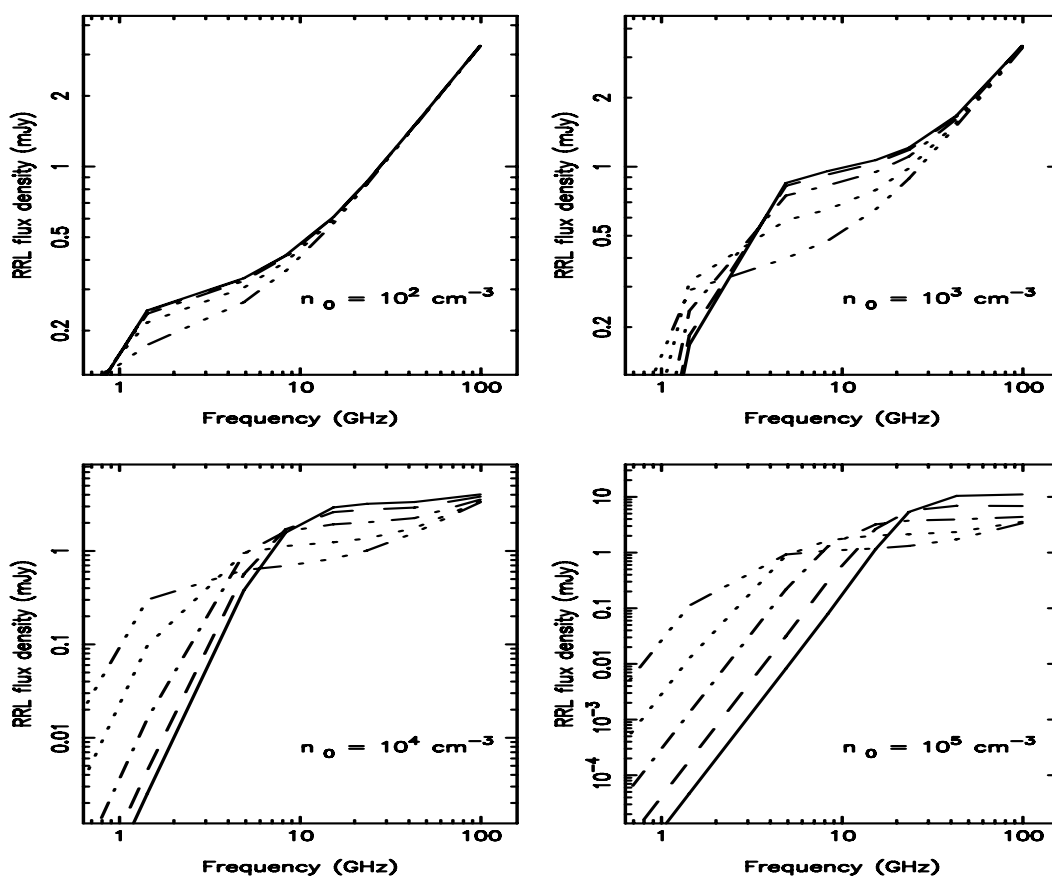


Figure 6.11: RRL flux density *vs.* frequency for various values of time t and ambient density n_0 . The solid, dashed, dash-dotted, dotted and dot-dot-dashed curves are for $t=10^4, 4\times10^4, 10^5, 6\times10^5$ and 2×10^6 years.

6.7 Summary

Five starburst galaxies (NGC 4038/9, NGC 1808, NGC 7552, II Zw 40 and VV 114) were observed at 8.3 GHz using the VLA in the C and D configurations in order to detect the H92 α recombination line. The line was detected in NGC 1808 but not detected in any of the others. The H92 α line in NGC 1808 is detected towards an off-nuclear continuum source. Models for the gas in this region yield a density of 10^3 - 10^4 cm $^{-3}$ and an effective size of 4-11 pc with an ionization rate of $(4-8)\times10^{52}$ s $^{-1}$. Using filling factors arguments, we conclude that this gas must be spread over an area larger than 40-70 pc, in the form of multiple star clusters. The maximum thermal fraction of the continuum emission is calculated for the other star forming sites in this galaxy using the upper limit to the line emission. The non-detection of recombination line emission from the other star forming sites in NGC 1808, though of comparable or even stronger Bry emission, is attributed to the relative youth of the starburst in the hotspot region and hence the presence of a larger amount of dense gas. The ionized gas in VV 114, II Zw 40, NGC 4038/9 and NGC 7552 were also modelled by using the upper limits to the H92 α line and the observed continuum flux densities and the maximum thermal fraction derived in each case. In NGC 4038/9 (the Antenna galaxies), most of the star formation is known to occur in an optically obscured region and the strongest radio continuum source in this region is 54.96-06.1. We derive the thermal fraction of the continuum at 8.3 GHz to be less than

60 % in this source, which is not consistent with the observed spectral index. Recently, four ‘supernebulae’ have been discovered in II Zw 40 through their radio continuum emission, all of which is possibly free-free radiation. Modelling the measured continuum flux densities from these sources indicates that they produce $\lesssim 70$ % of the derived 3σ upper limit to the H92 α line (the line fraction decreasing for increasing density). Since the detection of RRLs from supposedly similar supernebulae in NGC 5253 and Henize 2-10 have been used to constrain the dynamics and the age of these objects (see chapter 4), future observations of the RRL emission from II Zw 40 must be undertaken.

The H92 α luminosity is shown to be well correlated with the FIR luminosity (and hence also the total 1.4 GHz luminosity). The FIR flux of galaxies not detected in the H92 α line are comparable to the detected galaxies. For typical values of synthesized beam sizes and ionization rates, a given line emission is shown to be detectable from gas in a particular range of densities. However, a gas density of 10^4 cm^{-3} is derived for a few galaxies, independent of observational biases. The common occurrence of this density for nebulae around SSCs is explained in terms of a two-phase molecular ISM model. Lastly, it is shown that in the case of an HII region expanding due to overpressure, higher frequency RRLs are emitted preferentially at earlier times. Hence the starbursts in galaxies not detected in H92 α emission are either much older or younger than 10^5 - 10^6 years or the short term SFR (averaged over 10^5 - 10^6 years) is lesser than the long term SFR (averaged over $\gtrsim 10^6$ years).