

Chapter 5

NGC 3628 and Arp 299 (NGC 3690/IC 694): multi-line observations

5.1 Introduction

NGC 3628 and Arp 299 are examples of highly obscured infrared luminous galaxies undergoing vigorous starbursts. Arp 299 is composed of two galaxies, IC 694 and NGC 3690, which are interacting with each other. Zhao et al. (1997; hereafter ZAGV97) studied in detail the physical properties as well as the kinematics of the ionized gas in these systems at 1'' resolution using the H 2α recombination line at 8.3 GHz (see Anantharamaiah et al. 1993, hereafter AZGV, for earlier work at lower resolution). However, since only one recombination line was observed by ZAGV97, they could not unambiguously model the properties of the ionized gas. Based on the data, which were modelled as arising in a collection of uniform density HII regions, two classes of degenerate solutions were derived: low density (typically tens of HII regions with diameter ~ 5 pc and electron density of $\gtrsim 500$ cm $^{-3}$) and high density (typically about 10^5 HII regions of diameter ~ 0.05 pc and electron density of $\sim 5 \times 10^4$ cm $^{-3}$). Based on their prediction of the frequency dependence of the line strength using their models, they suggested that multi-frequency RRL observations could be used to decide between these two classes. Specifically, the low density models predicted detectable lines near 1 GHz whereas the high density models did not. We also expect the amount of high density gas to be better constrained through measurement of the RRL intensity at $\nu > 8$ GHz.

Therefore, to better constrain the properties of the ionized gas, we have observed NGC 3628 and Arp 299 using the Very Large Array (VLA) in order to detect RRL emission at 1.4 GHz and 15 GHz. We have also imaged the 330 MHz continuum emission from these galaxies to search for a turnover in the continuum spectrum due to free-free absorption.

NGC 3628 is a nearby ($D=11.5$ Mpc) edge-on Sbc galaxy and belongs to the Leo triplet of interacting galaxies. A dust lane is responsible for heavy dust obscuration of the central region. This galaxy exhibits a disturbed morphology and also possesses tails and plumes connecting it with the other members of the group (observed in HI : Haynes, Giovanelli, & Roberts 1979; optical : Kormendy & Bahcall 1974; FIR : Hughes, Appleton, & Schombert 1991). The central region of NGC 3628 is undergoing a starburst, evidenced by the high FIR luminosity (Lehnert & Heckman, 1996), strong extended radio emission (Condon et al., 1982), large amounts of

molecular gas, both CO (Israel, Maloney, & Baas, 1990; Boisse, Casoli, & Combes, 1987) and OH (Rickard, Bania, & Turner, 1982; Schmelz, Baan, & Haschick, 1987b) and outflows seen in various wavebands (Fabbiano, Heckman, & Keel, 1990). High resolution ($0.2''$ beam) imaging of the nuclear radio continuum emission at 15 GHz (Carral, Turner, & Ho, 1990) revealed the presence of a linear chain of about sixteen compact unresolved (size $\lesssim 8$ pc) sources, similar to the starburst galaxies NGC 253 and M 82. Cole, Mundell, & Pedlar (1998) presented HI absorption spectra against each of the compact sources using data from the MERLIN array at a similar resolution of $0.2''$. They compute high values ($>10^4$ K) of the brightness temperature for these sources and hence conclude that these are predominantly non-thermal in nature. HI (Schmelz, Baan, & Haschick, 1987a), OH (Schmelz, Baan, & Haschick, 1987b) and H_2CO (Baan & Goss, 1992) emission images consistently show the presence of two distinct kinematical features in the centre: a ~ 150 pc diameter ring and an anomalous structure, probably caused by interaction. ZAGV97, as mentioned earlier, have imaged the central region in the $\text{H}92\alpha$ recombination line at 8.3 GHz at a resolution of $1''$ and have discussed in detail both the ionized gas kinematics and the gas properties.

Arp 299 ($D=40$ Mpc) consists of two closely interacting galaxies, IC 694 and NGC 3690, also referred to as A and B (Gehrz, Sramek, & Weedman, 1983). Both these galaxies, as well as a gas rich overlapping region (which consists mainly of two components called C and C'), are undergoing a starburst. The star formation in this system, determined by the FIR luminosity and molecular gas mass, is dominated by IC 694, followed by NGC 3690 and then by the overlap region. The molecular gas in these galaxies has been imaged in detail (see Casoli 1999 and references therein). There exists numerous optical, NIR, MIR and FIR imaging and spectroscopic studies of each of the star forming sites in this system (Wynn-Williams et al., 1991; Keto et al., 1997; Lai et al., 1999; Satyapal et al., 1999; Sugai et al., 1999; Alonso-Herrero et al., 2000; Charmandaris, Stacey & Gull, 2002). The various star forming sites are known to have different ages and extinctions (Satyapal et al., 1999; Sugai et al., 1999; Alonso-Herrero et al., 2000). A number of massive star clusters are present in these galaxies and their luminosities and ionizing photon rates have been derived (Lai et al., 1999; Alonso-Herrero et al., 2000). ZAGV97 have imaged Arp 299 in the $\text{H}92\alpha$ recombination line at $1''$ resolution. Line emission was detected by them from IC 694 and a tentative detection exists towards NGC 3690 at the 3σ level.

5.2 Observations

Observations of the $\text{H}75\alpha$ line from NGC 3628 and $\text{H}76\alpha$ line from Arp 299 were carried out in the 15 GHz band using the VLA in the D configuration. The observational parameters are listed in Table 5.1. The continuum images of the two galaxies at 15 GHz are shown in figures 5.1a and 5.2a.

Bandpass calibration of the data was performed once every 1.5 hours. This was found not to be adequate to completely calibrate the well-known 3 MHz (60 km s^{-1} at 15 GHz) ripple present in the waveguide system and this limits the final dynamic range in each channel. The data were taken over two days and the second dataset was not used in the final spectral analysis due to problems with the time variations in the bandpass. The recombination line was detected towards the centre of NGC 3628 and the spectrum towards the peak of the continuum emission

Table 5.1: Observational and image parameters

Parameter	NGC 3628			Arp 299		
	15 GHz	1.4 GHz	330 MHz	15 GHz	1.4 GHz	330 MHz
Date of observation	01/05/99	26/03/1998	22/01/2001	01,10/05/1999	22/03/1998	22/01/2001
ν_{rest} of RRL (GHz)	15281.5	1399.4, 1374.6	—	14690.0	1424.7, 1399.4	—
Bandwidth (MHz), channels, IF	46.9, 15, 1	6.05, 31, 4	3.125	46.9, 15, 1	6.05, 31, 4	3.125
Spectral resolution ^a (km s ⁻¹)	123	85	—	129	85	—
Minimum baseline (k λ)	3.0	7	1.7	2.5	5	1.2
Synthesized beam (natural weighting)	7.1'' $\times$ 5.4''	1.8'' $\times$ 1.6''	6.5'' $\times$ 5.8''	5.7'' $\times$ 5.3''	1.8'' $\times$ 1.6''	5.7'' $\times$ 5.3''
P.A. of beam	85°	35°	120°	20°	-34°	23°
Phase calibrator (B1950.0)	1116+128	1119+183	1119-030	1150+497	1144+542	0834+555
Bandpass calibrator (B1950.0)	1055+018	1226+023	—	0836+710	0831+557	—
Peak continuum (mJy/beam)	39.7	45.2	97	60.8	130	232
Total continuum (mJy)	70	306	315	121	535	1500
Noise in continuum image (1 σ , μ Jy/beam)	96	60	3600	113	100	4000
Noise per channel ^a (μ Jy/beam)	270	110	—	300	115	—
Observed FWHM (km s ⁻¹)	270 ^b $\pm$ 60	—	—	274 $\pm$ 64	295 $\pm$ 100	—
Line strength ($\times 10^{-23}$ W m ⁻²)	12 ^b $\pm$ 2.5	—	—	15 $\pm$ 3	3.1 $\pm$ 0.9	—
Peak line strength (mJy)	0.82 ^b $\pm$ 0.17	—	—	1.1 $\pm$ 0.2	0.21 $\pm$ 0.06	—

^aAfter offline hanning smoothing.

^bUsing data for the first day only.

is shown in figure 5.3a. In Arp 299, we detect the $H76\alpha$ line only towards IC 694, and do not detect any emission towards either NGC 3690 or the overlapping C and C' regions. The spectrum towards the continuum peak of IC 694 is shown in Figure 5.3b.

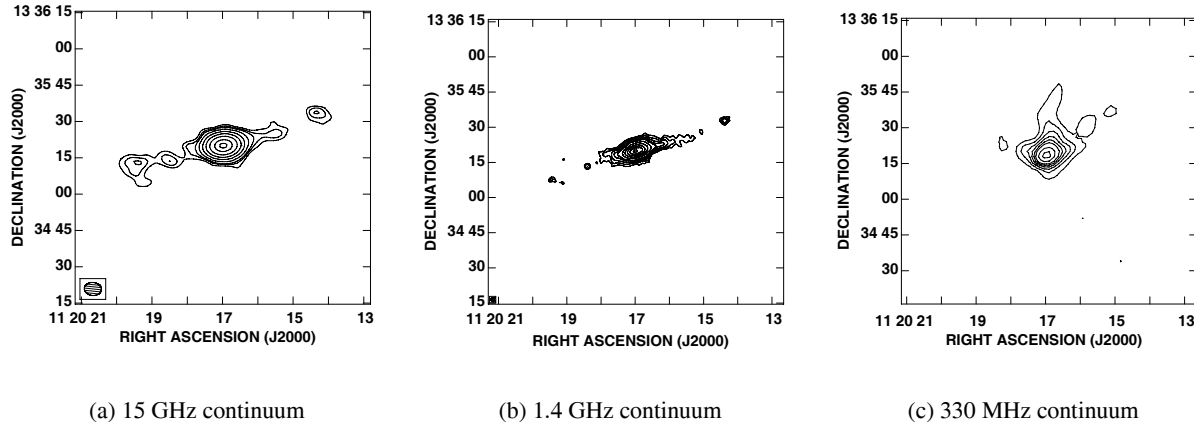


Figure 5.1: **(a).** The continuum emission of NGC 3628 at 15 GHz. The rms noise in the image is $100 \mu\text{Jy}/\text{beam}$ and the contour levels are (5, 7, 9, 15, 30, 60, 120, 240, 360) times the rms. The synthesized beam is $7.1'' \times 5.4''$ at a P.A. of 85° . **(b).** The continuum emission of NGC 3628 at 1.4 GHz. The rms noise in the image is $60 \mu\text{Jy}/\text{beam}$ and the contour levels are (5, 7, 10, 15, 20, 40, 80, 160, 320, 640) times the rms. The synthesized beam is $1.8'' \times 1.6''$ at a P.A. of 35° . **(c).** The continuum emission of NGC 3628 at 0.33 GHz. The rms noise in the image is $5 \text{ mJy}/\text{beam}$ and the contour levels are (-2, 2, 4, 6, 8, 10, 12, 16, 20, 24, 28, 32) times the rms. The synthesized beam is $6.5'' \times 5.1''$ at a P.A. of 120° .

The VLA in the A configuration was used to search for RRLs near 1.4 GHz ($H168\alpha$ and $H167\alpha$ from NGC 3628 and $H167\alpha$ and $H166\alpha$ from Arp 299) in the 4 IF mode of the correlator. The observational parameters are listed in Table 5.1. The continuum emission was imaged at a resolution of $\sim 1.6''$. Multiple fields were defined around strong continuum sources situated within an area of two primary beams and their continuum emissions were also simultaneously deconvolved, along with the emission from the galaxy, during the imaging process. The 1.4 GHz continuum images of NGC 3628 and Arp 299 are shown in figures 5.1b and 5.2b respectively. The continuum image of Arp 299 resolves most of the star formation sites in the system. Both at 1.4 GHz and at 15 GHz, the unusual point source IC694–2000 (see ZAGV97 and references therein), known to be strongly variable, is detected; the flux density is $1.1 \pm 0.1 \text{ mJy}$ at 1.4 GHz and $2.5 \pm 0.5 \text{ mJy}$ at 15 GHz. The effect of the 3 MHz ripple (640 km s^{-1} at 1.4 GHz) is seen to be much more pronounced at 1.4 GHz compared to 15 GHz and effectively limits the reliability of spectral features. We do not detect line emission towards NGC 3628 or NGC 3690. A line feature, which is spatially unresolved, is detected towards IC 694 at the 3.5σ level. The spectrum of the weak line emission is shown in figure 5.3c.

The 330 MHz continuum emission from both galaxies were imaged using the VLA in the A configuration with an angular resolution of $\sim 7''$. The observations were carried out in the line mode and the final images were constructed by bandwidth synthesis (i.e., gridding the visibilities of each channel separately to reduce bandwidth smearing) and emission from strong sources within two primary beam areas were deconvolved simultaneously. The tangent plane approximation was used to reduce the effects of non-coplanarity of the array during the course of the observations. Further parameters are listed in Table 5.1. The continuum images of NGC

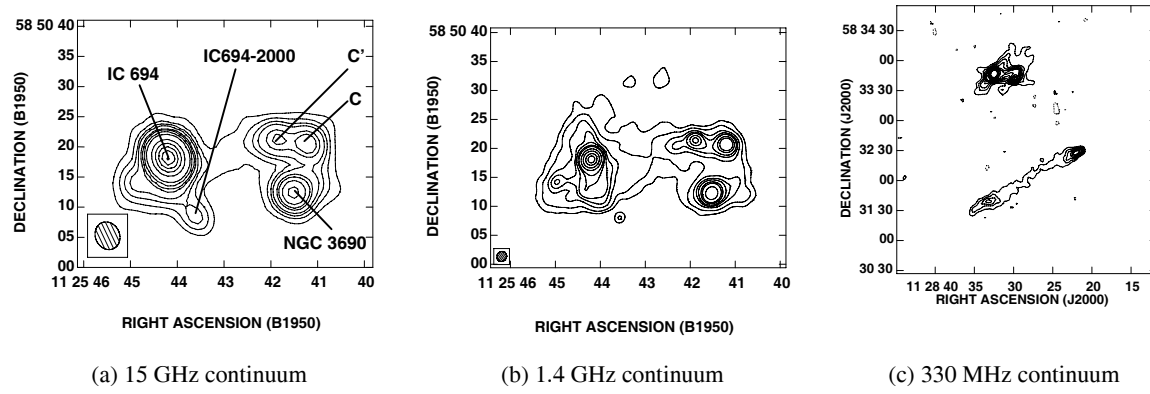


Figure 5.2: Continuum images of Arp 299 at **(a)**. 15 GHz. The rms noise is $140 \mu\text{Jy}/\text{beam}$ and the contour levels are (5, 10, 15, 20, 30, 37, 50, 70, 140, 210, 280, 350, 410) times the rms. The synthesized beam is $4.7'' \times 4.0''$ at a P.A. of 25° . **(b)**. 1.4 GHz. The rms noise is $100 \mu\text{Jy}/\text{beam}$ and the contour levels are (5, 10, 20, 30, 40, 60, 80, 160, 320, 640, 1000) times the rms, The synthesized beam is $1.8'' \times 1.6''$ at a P.A. of -34° . and **(c)**. 0.33 GHz. The rms noise is $4 \text{ mJy}/\text{beam}$ and the contour levels are (5, 10, 15, 20, 30, 37, 50, 70, 140, 210, 280, 350, 410) times the rms. The synthesized beam is $5.7'' \times 5.3''$ at a P.A. of 23° .

3628 and Arp 299 are shown in figures 5.1c and 5.2c respectively. The 330 MHz image of Arp 229 shows evidence for an extended halo around the entire system.

5.3 Modelling the ionized gas

Table 5.2: Modelling parameters

Frequency (GHz)	NGC 3628		IC 694 (2.5'')	NGC 3690 (1.3'')	Ref.
	Nucleus (3.2'')	(7.1'')			
Continuum parameters (mJy)					
0.33	< 108	< 110	<232	< 112	1
1.4	88	159	150	25	1
4.8	—	—	110	—	2
8.3	35	64	91	13	2
15.0	< 40	41	< 58	< 12	1
23.2	—	—	29	9	3
87.7	—	—	< 24	< 6	4
109.2	—	—	< 21	< 5	4
RRL parameters ($\times 10^{-23} \text{ W m}^{-2}$)					
1.4	< 0.47 ^a	< 0.95 ^a	0.3	< 0.13 ^a	1
8.3	4.4	11.4	7.2	1.6	2
15.0	< 12	12.0	15.1	< 3.7 ^a	1

NOTE: All upper limits indicate that the values are measured over a region whose size is larger than that modelled here, except those marked with a superscripted *a* which are non-detections.

1: This work; 2: ZAGV97; 3: Baan & Haschick 1990, ApJ, 364, 65; 4: Casoli et al. 1999, A&A, 346, 663

Though the 15 GHz line emission from NGC 3628 and IC 694 is spatially unresolved, higher resolution data (ZAGV97) show that this emission is in fact extended over a 100-300 pc region.

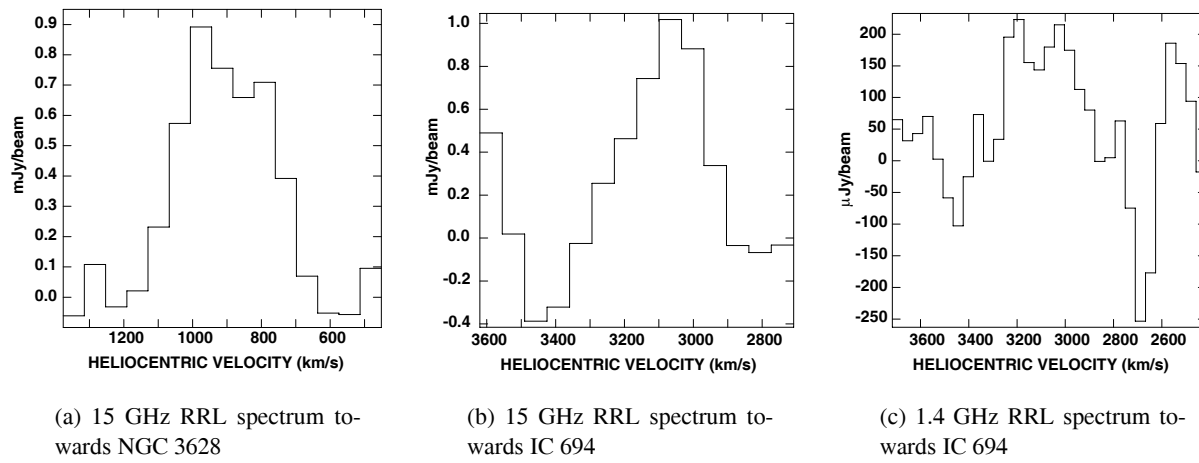


Figure 5.3: **(a).** Spectrum of H75 α line at 15 GHz towards the continuum peak of NGC 3628 with a velocity resolution of 123 km s⁻¹. The synthesized beam is 7.1'' $\times$ 5.4'' and the rms in the channel images is 0.27 mJy/beam. **(b).** Spectrum of H76 α line at 15 GHz towards the continuum peak of IC 694 with a velocity resolution of 129 km s⁻¹. The synthesized beam is 5.7'' $\times$ 5.3'' and the rms in the channel images is 0.3 mJy/beam. **(c).** Average of the spectra of H167 α and H166 α lines at 1.4 GHz towards the continuum peak of IC 694 with a velocity resolution of 85 km s⁻¹. The synthesized beam is 1.8'' $\times$ 1.6'' and the rms in the channel images is 0.11 mJy/beam. This weak line is a tentative detection at 3.5 σ level and needs to be confirmed.

We assume that the observed lines at 8.3 and 15 GHz arise in the same gas, spread over this region. This ionized gas is modelled both as a uniform slab of constant density (Model II) as well as a collection of single density HII regions (Model III).

5.3.1 NGC 3628

The continuum images of NGC 3628 in figures 5.1a and 5.1b and also the 8.3 GHz data in ZAGV97 do not have sufficient resolution to resolve the different compact components observed by Carral, Turner, & Ho (1990) and Cole, Mundell, & Pedlar (1998). Hence the specific sources responsible for the observed RRL emission cannot be identified. ZAGV97 decomposed the H92 α line emission into three spatial regions, termed the nucleus, the SE and the NW components, based on images at 1'' resolution. The angular resolution of the 15 GHz and 1.4 GHz images presented here are 6.3'' and 1.7'' respectively, with line emission detected only at the higher frequency. We use these data to model both the nucleus as well as the entire line emitting region.

The nuclear region, as identified by ZAGV97, is about 3.2'' (180 pc) in size. The continuum and the upper limit to the line (assuming an FWHM of 250 km s⁻¹) at 1.4 GHz are measured by convolving the images to this resolution. The RRL detected at 15 GHz over a 6.3'' region is taken as an upper limit in this analysis. The continuum and line constraints used in the modelling procedure are summarised in table 5.2. The compact continuum sources detected using a resolution of 0.2'' are dominated by non-thermal emission (Carral, Turner, & Ho, 1990; Cole, Mundell, & Pedlar, 1998). Since none of the compact sources are observed to be predominantly thermal in nature, the 1.4 GHz and 15 GHz free-free intensities predicted by the models must not exceed the typical brightness of the continuum sources. The area filling factor of the line

emitting gas within the synthesized beam is less than unity for all allowed models solutions. Hence, the constraint on the free-free intensity needs to be corrected for filling factor. Assuming conservatively that the thermal gas is equally distributed in every $0.2''$ sized area within the synthesized beam, this condition is recast as an upper limit on a quantity defined as

$$I' = \frac{S_{ff}}{(L^2/D^2)} \times \left(\frac{0.2'' \times 0.2''}{(\text{radian/arcsec})^2} \right) \times \left(\frac{0.2'' \times 0.2''}{3.2'' \times 3.2''} \right) \quad (5.1)$$

in the case of Model II. For Model III, S_{ff} is replaced by S_{ff}/f_1 , where f_1 is defined in section 2.3.1, and L is replaced by B . S_{ff} is the free-free flux density, 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 quantity I' has to be less than ~ 1.5 mJy at 15 GHz and less than ~ 2.0 mJy at 1.4 GHz, based on the high resolution images. A similar constraint on the non-thermal emission can also be imposed on the solutions. The model solutions predict the observable non-thermal intensity, corrected for absorption by the line emitting gas. Models with different geometries will yield different values for this quantity since the lateral extent of the non-thermal emission is one of the free parameters in these models. As in eqn. 5.1, the filling factor corrected intensity of this observable non-thermal emission is calculated and is constrained not to exceed, as a conservative estimate, the maximum intensity observed with a $0.2''$ beam. An electron temperature of 5000 K is assumed in the models. Using the continuum observations of Carral, Turner, & Ho (1990), Cole, Mundell, & Pedlar (1998) and ZAGV97, we estimate that about 40 % of the 8.3 GHz continuum emission in the $3.2''$ region is in the form of compact sources and the remaining is probably extended emission. It is tempting to utilize the known positions and intensity distribution of the non-thermal emission in the models to calculate the possible stimulated emission component of the recombination line emission. The results of such a model could be compared with the available continuum and line images as an added constraint on the line emitting gas. However, the RRL models yield consistent solutions even if the background radiation causing stimulated emission is assumed to be zero. Hence we do not include the observed distribution of the non-thermal emission in the models.

The range of densities obtained is similar for Models II and III and is between 500 – 10000 cm^{-3} . The volume occupied by the thermal gas is also similar, and its value is discussed later in this section. The predicted frequency dependence of the continuum and recombination line emission for typical solutions to Model III are shown in figure 5.4. The derived values of physical and radiation parameters for typical solutions are summarised in table 5.3. If the line measurements at 1.4 GHz and 15 GHz are not included as constraints in the model, then the allowed range of densities is increased to 50 – 50000 cm^{-3} . The higher density solutions ($n_e > 10^4$ cm^{-3}) are excluded by the 15 GHz line measurements. Based on their models, ZAGV97 claimed that the low density solutions can be constrained by low frequency recombination lines, i.e., detection of the 1.4 GHz line would favour the low density models and vice versa. As expected, the largest values of the predicted 1.4 GHz line strength occur for the lowest densities, and can be as high as 65-90 % of the observed upper limit to the line emission for $n_e \leq 10^3$ cm^{-3} . Therefore, the upper limits from the 1.4 GHz observations are not sensitive enough to distinguish between low and high density models. However, an improved sensitivity of the line data by a factor of two to three could distinguish between the two classes of densities : 500 – 3000 cm^{-3} and 3000 – 10000 cm^{-3} . The derived ionization rate lies between 6×10^{52} and

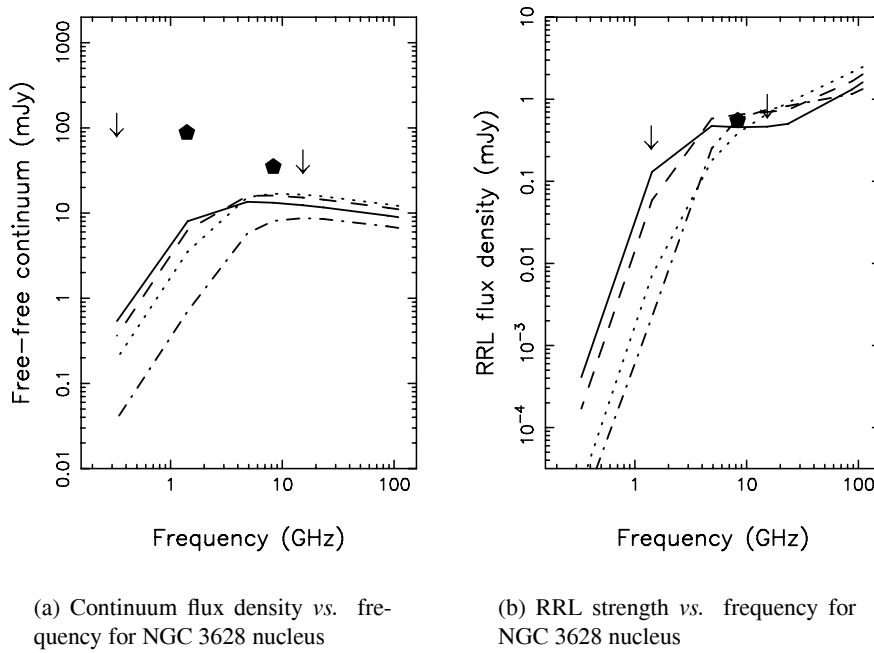


Figure 5.4: The predictions of typical solutions for the frequency dependence of **(a).** continuum and **(b).** line flux densities for the nucleus of NGC 3628, in Model III (collection of constant density HII regions) for $T_e=5000$ K. The non-thermal radiation is assumed to fill the beam and to be behind the thermal gas. The imposed constraints (detections and upper limits) are indicated as filled pentagons and arrowmarks. The arrows in (5.4a) indicate that the plotted continuum flux densities are determined for a region larger than the area modelled here and the arrows in (5.4b) indicate the 3σ upper limits to the undetected line emission. The solid, dashed, dotted and dash-dotted curves are, respectively, for $n_e=500 \text{ cm}^{-3}$, $l=3.3 \text{ pc}$, $N=4000$, $B=73 \text{ pc}$; $n_e=1000 \text{ cm}^{-3}$, $l=3.2 \text{ pc}$, $N=1300$, $B=61 \text{ pc}$; $n_e=5000 \text{ cm}^{-3}$, $l=2.5 \text{ pc}$, $N=68$, $B=51 \text{ pc}$ and $n_e=10000 \text{ cm}^{-3}$, $l=0.2 \text{ pc}$, $N=65000$, $B=73 \text{ pc}$.

$3.5 \times 10^{53} \text{ s}^{-1}$ and for most solutions, the value is $(1-2) \times 10^{53} \text{ s}^{-1}$. The ionization rate is found to be correlated with the free-free continuum flux density. Based on the spectral index, the cm-wave continuum emission from the compact sources in the central $3.2''$ region is predominantly non-thermal. Hence, if we assume that the fraction of the total 8.3 GHz continuum emission which is contributed by the free-free emission from the line emitting gas is not more than, say, 20 % (since a much higher fraction would lead to a flatter spectral index than observed), then the ionization rate is constrained to be less than $2 \times 10^{53} \text{ s}^{-1}$. The mass of the ionized gas depends on the assumed density. The derived values are about $6 \times 10^5 M_\odot$ for the low density solutions and about $4 \times 10^4 M_\odot$ for the high density solutions. The effective size of the line emitting gas decreases with increasing density. For the low density models, the effective size (volume $^{1/3}$) is about 40-50 pc while for the high density models, the effective size is $\leq 10 \text{ pc}$. Based on the constraint on the free-free intensity for a $0.2''$ (11 pc) beam (see eqn. 5.1), the thermal gas must be spatially spread over a larger region in the form of individual HII region complexes, and hence have a small filling factor. Hence more than one star cluster, each spatially well separated, is required to ionize the line emitting gas. Though IR imaging has indeed detected a host of star clusters in NGC 3628, we cannot readily associate these IR clusters with the ionizing sources for the line emission since these clusters are probably too old to retain significant amounts of gas in their environments. The existing radio continuum and RRL data do not allow us to constrain the ionized gas properties or the detailed star formation history to a much narrower range.

ZAGV97 found the line emitting region to be spread over an area of effective size $7''$ which consists of the nucleus, the SE and the NW regions. Since the resolution of the 15 GHz data is close to $7''$, we also model the entire line emitting region as a thermal gas with uniform properties. The 15 GHz and 1.4 GHz data were convolved to $7''$ resolution and the continuum and line parameters were determined. The model solutions were obtained for a temperature of 5000 K. The allowed density range for Model II is $500\text{-}10000\text{ cm}^{-3}$ whereas for Model III, the range is narrower, $500\text{-}1000\text{ cm}^{-3}$. The value of the ionization rate lies in the range $(2\text{-}10)\times 10^{53}\text{ s}^{-1}$ and that of the ionized gas mass in the range $10^5\text{-}2\times 10^6\text{ M}_\odot$. The derived densities, emission measures and the ionization rate are within a factor of two of the values derived for the nucleus alone. Hence, the physical properties of the ionized gas in the SE and NW regions are probably similar to those of the nucleus. RRL observations at 15 GHz which spatially resolve the three star forming regions are required in order to construct more detailed models.

Table 5.3: Derived parameters for NGC 3628 and Arp 299
(Model III, $T_e=5000\text{ K}$)

Density (cm^{-3}) (1)	l_{eff} (pc) (2)	τ_c^{los} (3)	$N_{\text{Lyc}}(\times 10^{53}\text{ s}^{-1})$ (4)	$M_{\text{HII}}(\times 10^5\text{ M}_\odot)$ (5)	f_{th} (8.3 GHz) (6)	Stim. em. % (7)	f_{line} (1.4 GHz) (8)	f_{line} (15 GHz) (9)
<i>NGC 3628^a (3.2'' sized nucleus, as identified by ZAGV97); $D=11.5\text{ Mpc}$</i>								
500	45-60	0.02-0.1	1.6-3.6	6-13	0.25-0.6	0-10	0.2-0.65	0.45-0.8
1000	25-37	0.03-0.2	1.1-3.5	2-6.5	0.2-0.6	0-9	0.05-0.3	0.45-0.9
5000	7-12	0.1-1.4	0.6-3.0	0.2-1.2	0.07-0.5	0-3.5	0-0.06	0.6-1
10000	5-8	0.2-2 ^b	0.9-3.5	0.15-0.6	0.07-0.5	0-2	0-0.02	0.75-1
<i>IC 694 (2.5'' region); $D=40.3\text{ Mpc}$</i>								
400	150	0.08	30-40	170	0.2	40	1	0.7
2000	60	0.04	50-60	50	0.3	30	0.8	0.9
<i>NGC 3690 (unresolved galaxy); $D=40.3\text{ Mpc}$</i>								
300	100-120	0.04-0.08	6-10	40-60	0.25-0.35	22-28	0.6-1	0.3-0.7
8000	10-15	0.4-2 ^b	4-12	0.8-3	0.05-0.45	2-5	0-0.02	0.9-1

^aSince the range of allowed densities for NGC 3628 is large, we have tabulated quantities for various values of density. These solutions correspond to various possible configurations of the non-thermal and thermal gas.

^bIf the range of the line-of-sight optical depth is large, it is found that, within the allowed range listed in the table for various quantities, the line-of-sight optical depth varies inversely as the quantities in columns (2), (4), (5), (6) and (7), as expected.

(1) The first and second row for IC 694 and NGC 3690 correspond to typical models from the low density and high density ends of the allowed range respectively; (2) Effective size, defined as $N^{1/3} l$; (3) Line-of-sight free-free optical depth, $\tau_c \times f_2$, where f_2 is defined in section 2.3.1; (4) Ionization rate; (5) Mass of ionized gas; (6) Ratio between predicted free-free emission to total observed continuum at 8.3 GHz; (7) Percentage of 8.3 GHz line emission due to stimulated emission by background non-thermal radiation, assumed to fill the beam; (8) Ratio between predicted 1.4 GHz RRL emission and observed value (detected or upper limit); (9) Ratio between predicted 15 GHz RRL emission and observed value (detected or upper limit).

The total 330 MHz flux density is 350 mJy. This value is estimated to be about 35 % of the total flux density at this frequency (by interpolating from multifrequency continuum data taken from the Nasa Extragalactic Database). However, the continuum emission over the central $10''$ is not expected to suffer from missing short uv spacings in the data and is hence reliable. The 330 MHz continuum emission from this region indicates a turnover in the spectrum, probably due to free-free absorption. The fraction of non-thermal radiation covered by the RRL emitting thermal gas, i.e., the covering factor of this gas, is much less than unity and hence this thermal component cannot explain the observed turnover. Hence an additional component of ionized gas, apart from that which is responsible for the observed cm-wave RRLs, is necessary. Assuming an intrinsic spectral index of -0.7 for the non-thermal emission, the free-free optical depth for this component at 330 MHz is derived to be 1.0 for a foreground screen and 2.5 for spatially co-existent thermal gas, assuming unit covering factor. Models for such a component

yield no solution consistent with the line and continuum data at other frequencies. Hence the observed turnover is probably caused by gas which cannot be modelled as above, i.e., as having a single density and/or unit covering factor. Therefore, we suggest that there is some evidence for multiple components of the ionized gas in NGC 3628. An actual detection of the 1.4 GHz RRL and higher resolution observations of the 15 GHz line coupled with the low frequency continuum data might well lead to the construction of a multi-component model, similar to that of NGC 253 (see chapter 4) and Arp 220 (Anantharamaiah et al., 2000).

5.3.2 IC 694

IC 694 ($D=40.3$ Mpc) is the most intense star forming component of Arp 299. The 8.3 GHz RRL (ZAGV97) and also the 15 GHz RRL (this work) have been detected towards this galaxy along with a tentative detection of the 1.4 GHz RRL as well.

ZAGV97 identified two regions of line emission in this galaxy, the nucleus and the SE region. We model all of the line emitting region, i.e., both the nucleus and the SE extension, as one unit of size $\sim 2.5''$ (490 pc). Continuum data from 330 MHz to 110 GHz, as well as the line data, are tabulated in Table 5.2. Treating the 1.4 GHz line (which is observed at the 3.5σ level) as a detection, we model the ionized gas in IC 694 based on the assumption that all three lines arise in a single ionized gas component at a fixed density.

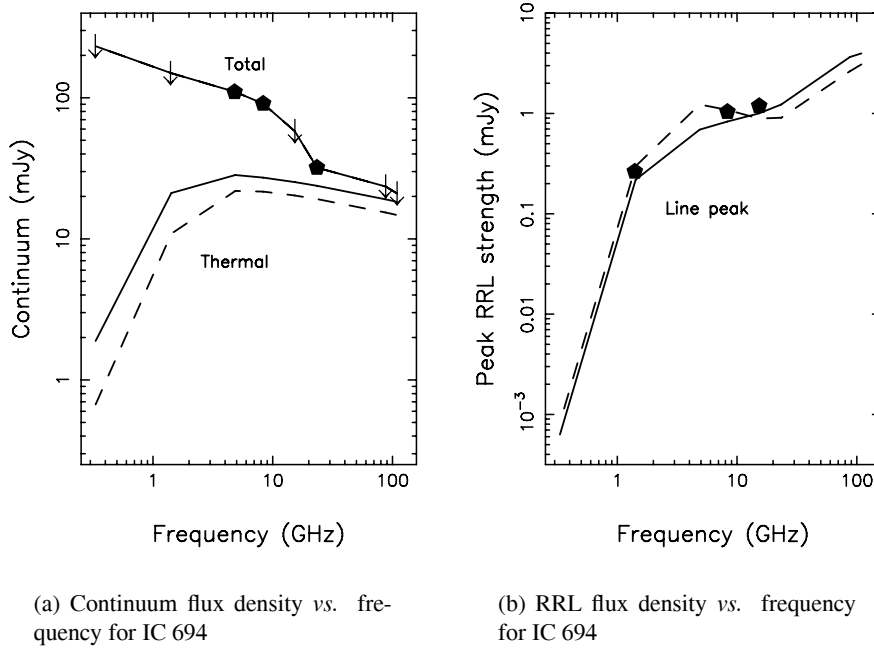


Figure 5.5: The predictions of typical solutions for the frequency dependence of **(a)**. continuum and **(b)**. line flux densities for the nucleus of IC 694, in Model III (collection of constant density HII regions) for $T_e=5000$ K. The imposed constraints (detections and upper limits) are indicated as filled pentagons and arrowmarks. The arrows in (5.6a) indicate that the plotted continuum flux densities are measured for a region larger than the area modelled here and the arrows in (5.6b) indicate the 3σ upper limits to the undetected line emission. The solid curve corresponds to the model $n_e=2000 \text{ cm}^{-3}$, $l=0.6 \text{ pc}$, $N=10^6$, $B=600 \text{ pc}$ in which the non-thermal radiation is assumed to be behind the thermal gas. The dashed curve corresponds to a model where $n_e=300 \text{ cm}^{-3}$, $l=23 \text{ pc}$, $N=620$, $B=290 \text{ pc}$ in which the non-thermal radiation is assumed to be in front of the thermal gas.

A uniform rectangular slab of thermal gas cannot satisfy all of the line emission constraints for any combination of parameters. However, a collection of HII regions can satisfy the imposed constraints for values of density in the range $300\text{--}3000\text{ cm}^{-3}$. The ionization required ranges between $(3\text{--}15)\times 10^{54}\text{ s}^{-1}$. The number of HII regions and the size of each region vary over a wide range of values for the derived solutions, constrained by the condition that the line of sight continuum optical depth ($f_2\times\tau_c$ where τ_c is the optical depth of an individual HII region) at 8.3 GHz is within the range 0.03–0.10. The transverse length of the line emitting region ranges between 230–550 pc ($1.2''\text{--}2.8''$). Typical values for the derived parameters of the thermal gas are listed in table 5.3 and the predicted continuum and line emissions for typical model solutions are shown in figure 5.5. Though both the 1.4 GHz as well as the high frequency lines can be explained by gas at a single density, it does not necessarily follow that all three lines have a common physical origin. Additionally, the 1.4 GHz RRL detection is tentative and needs to be confirmed. Hence, we also model the ionized gas with the 1.4 GHz line emission taken as an upper limit rather than a detection. In this case, the upper limit to the allowed density is higher ($\sim 30000\text{ cm}^{-3}$). Solutions with even higher density are also obtained for which the ionization rate is as low as $3\times 10^{52}\text{ s}^{-1}$. No significant turnover in the continuum intensity between 1.4 GHz and 330 MHz is observed in IC 694.

5.3.3 NGC 3690

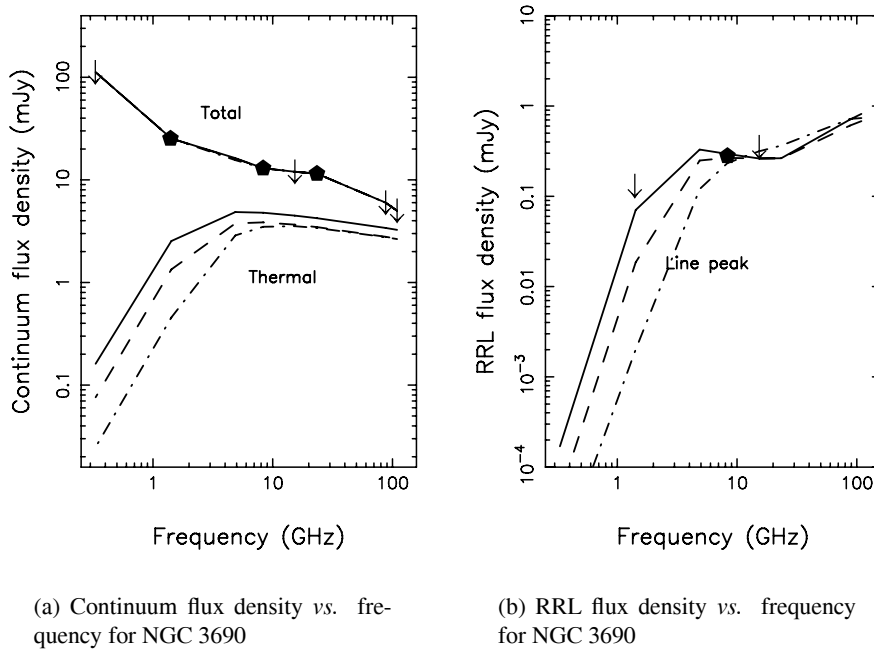


Figure 5.6: The predictions of typical solutions for the frequency dependence of (a). continuum and (b). line flux densities for the nucleus of NGC 3690, in Model III (collection of constant density HII regions) for $T_e=5000\text{ K}$. The imposed constraints (detections and upper limits) are indicated as filled pentagons and arrowmarks. The arrows in (5.5a) indicate that the plotted continuum flux densities are measured for a region larger than the area modelled here and the arrows in (5.5b) indicate the 3σ upper limits to the undetected line emission. The non-thermal radiation is assumed to be behind the thermal gas. The solid, dashed and dash-dotted curves correspond to $n_e=500\text{ cm}^{-3}$, $l=13\text{ pc}$, $N=270$, $B=150\text{ pc}$; $n_e=1000\text{ cm}^{-3}$, $l=6\text{ pc}$, $N=590$, $B=105\text{ pc}$ and $n_e=5000\text{ cm}^{-3}$, $l=1.1\text{ pc}$, $N=3800$, $B=75\text{ pc}$.

NGC 3690 ($D=40.3$ Mpc) is the second strongest star forming region in Arp 299. We have modelled the tentative detection at 8.3 GHz and the upper limits to the line emission at 1.4 GHz and 15 GHz, along with the continuum spectrum from 1.4 GHz up to 108 GHz. The values of these constraints are listed in table 5.2. The derived range of gas densities consistent with the imposed constraints is $200\text{--}10000\text{ cm}^{-3}$, a smaller range compared to models which exclude the new line observations. Details of a typical low density and a typical high density solution obtained using Model III are listed in table 5.3. The obtained ionization rate is in the range $(2\text{--}30)\times 10^{53}\text{ s}^{-1}$. The larger values of the derived N_{Lyc} correspond to lower densities ($<5000\text{ cm}^{-3}$) and vice versa. Lai et al. (1999) derive an N_{Lyc} of $2.5\times 10^{54}\text{ s}^{-1}$ based on their $2.2\text{ }\mu\text{m}$ photometry which is consistent with our derived range for the ionization rate. However, since the sources of IR emission and RRL emission need not coincide (as in NGC 253), we do not attempt to constrain the dust extinction. Solutions for which the density lies at the higher end of the allowed range predict an RRL strength at 15 GHz which is about a factor of two lower than the upper limits obtained and hence can possibly be constrained by future more sensitive observations. Figure 5.6 shows the predicted peak line strength as a function of frequency for various densities for Model III.

5.4 Discussion

ZAGV97 derived a wide range of possible densities for the ionized gas in these galaxies. In all three galaxies (NGC 3628, IC 694 and NGC 3690), our models for the multiline data yield a narrower range since the very low and the very high density solutions can be eliminated. This range excludes densities less than a few 100 cm^{-3} and also densities more than a few 1000 to 10^4 cm^{-3} . The derived values of density correspond to those of compact HII regions in the Galaxy. The range of possible values of the ionization rate, however, is much smaller than that of gas density, partly because the continuum optical depth does not reach values large enough for the relation between the line (and continuum) emission and the ionization rate to become significantly nonlinear. This narrow range in the ionization rates $N_{\text{Lyc}} (\propto n_e^2 l_{\text{eff}}^3)$ could arise due to a much wider range in both n_e and effective size. However, the allowed range of gas densities, and hence the range of effective sizes, is limited in the model mainly by the constraints on the line emission at 1.4 GHz and 15 GHz. This limitation on the range of possible values arises primarily due to two reasons. One of them is the density dependence of the non-LTE factor and hence of the amount of line enhancement, especially in moderately optically thick cases, The other is the limitation on the high frequency continuum emission. However, for a given effective size, the values of the number N of HII regions and their diameters l are highly degenerate with each other. The maximum extent of the allowed solutions in the $N-l$ parameter space is limited by two factors: the total size of the line emitting region and hence the line of sight optical depth, and also because there has to be atleast one O star per HII region. The latter constraint implies that the minimum size of an individual HII region in the case of NGC 3628, NGC 3690 and IC 694 is 0.1 pc, 0.3 pc and 1.1 pc respectively.

The allowed values of densities for NGC 3628 and IC 694 share an overlapping range. The ratio between the $\text{H}75\alpha$ luminosity and the $\text{H}92\alpha$ luminosity is 1.1 for NGC 3628 and 2.1 for IC 694. The value of this ratio obtained for the various model solutions for NGC 3628 increase with density as expected: 0.6-1 for $n_e=500\text{ cm}^{-3}$ to 1.1-1.4 for $n_e=10^4\text{ cm}^{-3}$. Similarly, the

line ratio is 1.3-1.4 for $n_e=400 \text{ cm}^{-3}$ to ~ 2.2 for $n_e=2000 \text{ cm}^{-3}$. The rather wide range of the allowed line ratio arises from the large uncertainties in the measured quantities. However, the densities for which this ratio does equal the observed value of 1.1 and 2.1 for the two galaxies respectively are $\sim 5000 \text{ cm}^{-3}$ for NGC 3628 and $\sim 1500 \text{ cm}^{-3}$ for IC 694. A larger $\text{H}76\alpha/\text{H}92\alpha$ ratio might be expected to correspond to a larger density whereas the opposite behaviour is observed for these two galaxies. However, as can be seen in figure 2.4, for a particular value of the gas density, this line ratio depends sensitively on the continuum optical depth as well. In the case of NGC 3628, the average optical depth for $n_e=5000 \text{ cm}^{-3}$ is ~ 0.5 whereas, for IC 694, the average optical depth for $n_e=1500 \text{ cm}^{-3}$ is ~ 0.03 , which explains the observed trend of density versus line ratio in these two galaxies. If the gas density in NGC 3628 is indeed higher than in IC 694, two possible causes can be thought of. The density of the molecular gas in the nucleus of NGC 3628 could be higher than in IC 694. Alternatively, if the ambient densities are assumed equal, then the difference can be attributed to the latest (sub)peak in star formation in NGC 3628 being younger than in IC 694, since not enough time would have elapsed in the former galaxy for the HII regions to expand and become less dense.

NGC 3628 and Arp 299 are at distances of 11.5 and 40.3 Mpc respectively. If NGC 3628 were placed at the distance of Arp 229, its RRL flux density would be below the detection threshold of our observations. The luminosity of the $\text{H}92\alpha$ line by NGC 3628 is half that of NGC 3690, and their total FIR luminosities are comparable. It is more fruitful however to compare the various star forming sites within Arp 299. Using the 8.3 GHz line data, the various components can be ranked in descending order of line strength as IC 694 (A), NGC 3690 (primarily B1 but also includes B2) and then C and C'. This order is also, in decreasing value, the order of the SFR, M_{OB} , L_{FIR} and Σ_{H_2} (Alonso-Herrero et al., 2000). However, this order corresponds to a decreasing order of age (Alonso-Herrero et al., 2000). Differences in a given RRL strength can arise in one of the following ways: (1) in a constant SFR model, the value of the SFR and hence the total ionization is different; (2) for an instantaneous SFR, the ages of the starbursts is different and hence the total ionization is different; (3) the molecular gas densities are different and hence for a given line, the amount of gas in a particular density range is different. We rule out the second option since in such a scenario, the younger burst would be expected to be stronger in RRLs, opposite to what is observed. The third option cannot be ruled out but is considered relatively unlikely since there is no indication of a large change in line ratios between 1.4, 8.3 and 15 GHz (even accounting for upper limits). A more sensitive detection of the 1.4 GHz line in these galaxies along with a search for mm-wave RRLs would help constrain this scenario. Since the RRL strength is proportional to the SFR and the IR luminosity of these three star forming systems, we are inclined to favour the first scenario as the simplest explanation for the difference between these sites of star formation.

The motivation for the project described in this chapter was to derive the properties of the ionized gas in these galaxies to within a narrower range than in the single-line study of ZAGV97, and also to attempt to construct a multi-density model of the gas through multi-line data. The density and size of the line emitting region in IC 694 was indeed constrained much better than before. However this was not possible in the other two galaxies studied, partly because the 1.4 GHz and 15 GHz lines were not detected from all of the galaxies. Hence the modelling constraints were, for the most part, upper limits rather than actual line intensities. A study of the parameter space indicates that a factor of two to four improvement in sensitivity at these

frequencies is required in order to detect these lines, or obtain more meaningful constraints. Such an improvement would require a much larger amount of observing time than obtainable. A better strategy might be to eliminate the 3 MHz ripple, leading to a significant improvement in the signal to noise ratio of the line emission. The proposed Expanded VLA project will be able to do so, by replacing the waveguides by fibre-optic cables and a repetition of these observations with such a system would prove fruitful.

5.5 Summary

The starburst galaxies NGC 3628 and Arp 299 (consisting of IC 694 and NGC 3690) were observed using the VLA in order to detect recombination lines at 15 GHz and 1.4 GHz. The 330 MHz continuum emission from these galaxies was also imaged in order to detect a possible turnover in the emission due to free-free absorption. A multi-line analysis was undertaken in order to derive the ionized gas properties in these galaxies to a much better accuracy compared to earlier models based on a single RRL at 8.3 GHz (ZAGV97). The 15 GHz lines were detected towards NGC 3628 and IC 694 and a tentative detection of the 1.4 GHz line was obtained towards IC 694. Since the spatial resolution of the 15 GHz data is $\sim 6''$, the individual line emitting regions cannot be identified at present. For NGC 3628, similar parameters were obtained when the ionized gas was modelled in terms of an uniform slab or as a collection of HII regions. The values of the physical parameters of the ionized gas could be determined to within a narrower range due to the new multiple line constraints. The range of N_{Lyc} is much narrower than that of density. Models for the ‘nucleus’ of NGC 3628, as identified by ZAGV97, indicate that the line arises in gas whose density is between $500\text{--}10000\text{ cm}^{-3}$ with an ionization requirement of $(4\text{--}20)\times 10^{52}\text{ s}^{-1}$. This gas must have a filling factor significantly less than unity. An improved measurement of the 1.4 GHz recombination line (by a factor of 2-3) would help constrain the existence of gas in the lower density part of the derived range. The 330 MHz data indicates a significant amount of free-free absorption in the central part of the galaxy. Modelling this absorption, consistent with the measured line and continuum data at other frequencies shows that the absorbing gas must either exhibit a significant range of densities or must have a covering factor less than unity. The absorption due to the RRL emitting gas, however, is negligible. Modelling the entire line emitting region in NGC 3628 shows that the gas properties in the SE and NW regions are probably very similar to those for the nuclear region. Models constructed for NGC 3690 show that the allowed range in density is $200\text{--}10000\text{ cm}^{-3}$ with an ionization between $(2\text{--}30)\times 10^{53}\text{ s}^{-1}$. The ionized gas in the nucleus and the SE extension of IC 694 were modelled together. The observations could be explained only by a collection of HII regions. Solutions were found which could produce all of the observed emission in all the three lines detected. The density was constrained to a range of $300\text{--}3000\text{ cm}^{-3}$, assuming the 1.4 GHz line as a detection.

The derived gas density in NGC 3628 is higher compared to IC 694, which could be either due to differing molecular gas densities or different ages of the latest peak in star formation. However, for Arp 299, the different line strengths among the various star forming sites can be attributed to different SFRs rather than to either of these possibilities. For all star forming systems modelled in this chapter, the predicted 1.4 GHz and 15 GHz line flux densities for the non-detections are a factor of two to four less than the derived upper limits. More sensitive

observations would help constraining the gas parameters better and possibly also lead to the construction of a multi-density model of the ionized gas component of the ISM in these galaxies, much like in NGC 253 (see chapter 3) or Arp 220 (Anantharamaiah et al., 2000).