

Chapter 3

NGC 253 : high-resolution multi-line observations of a nearby starburst

3.1 Introduction

NGC 253 is a nearby ($D=2.5$ Mpc) highly inclined ($i=78^\circ$; Pence 1981) spiral galaxy. Rieke & Low (1975), Rieke et al. (1980) and Waller, Kleinmann & Ricker (1988) showed that the star formation rate is enhanced in the central ~ 100 pc, which dominates the total energetics of the galaxy. Far from it being a merely fashionable idea (Rieke et al., 1980), it has now been conclusively shown that NGC 253 is undergoing a starburst in the central region ($L_{\text{FIR}}=3\times 10^{10} L_\odot$; Telesco & Harper 1980), and is considered a prototype of the class StarBurst Nuclear Galaxies (SBNG). Canzian, Mundy & Scoville (1988) discovered a molecular bar in the galaxy and a corresponding infra-red bar has also been detected (Scoville et al., 1985). Both CO emission (see Harrison, Henkel & Russel 1999 for a review) as well as tracers of dense molecular gas (Peng et al. 1996 and Huettemeister, Mauersberger & Henkel 1997 along with earlier work by the latter group) have been studied in detail. The OH line has been detected both in absorption as well as in maser emission (see Frayer, Seaquist & Frail 1998 for a review). There have been numerous studies of the HI gas in NGC 253 (Huchtmeier 1972; see also Koribalski, Whiteoak & Houghton 1995 and references therein). NGC 253 is a X-ray bright galaxy and most of the observed X-ray emission arises in a large scale superwind (McCarthy, van Breugel, & Heckman, 1987; Forbes et al., 2000; Strickland et al., 2000). The small-scale X-ray emission has also been imaged in detail (see Pietsch et al. 2001 and references therein, and also Weaver et al. 2002). The kinematics of the ionized gas component has been studied using optical and IR lines (Beck & Beckwith, 1984; Puxley & Brand, 1995; Prada et al., 1996; Arnaboldi et al., 1995). The ionized gas in this region, studied by the emission in the radio, infra-red and the optical, consists of both compact and diffuse components and is distributed along a highly inclined ring. Turner and Ho (1985) discovered a string of compact sources at 15 GHz, which were studied in detail by Antonucci & Ulvestad (1988) and Ulvestad & Antonucci (1997). NGC 253 also has a radio halo whose low frequency emission was imaged by Carilli et al. (1992) and Carilli (1996). A number of infra-red (IR) hotspots have been detected in this region (Forbes et al., 1991, 1993; Piña et al., 1992; Keto et al., 1993; Sams et al., 1994; Kalas & Wynn-Williams, 1994). Kalas & Wynn-Williams (1994) and Sams et al. (1994) showed that most of these hotspots are actually regions of low dust extinction and are not coincident with the radio sources. Optical imaging by Watson et al. (1996) revealed the presence of four star clusters, which were identified with indi-

vidual IR knots (see also Forbes et al. 2000). The radio and the IR-optical sources seem to trace different populations of objects, presumably supernova remnants and HII regions, respectively.

The peak of the IR emission is offset by about $3.5''$ southwest from the peak of the radio continuum emission (the radio nucleus). There is no prominent radio emission associated with the IR peak and weak IR emission is observed near the radio nucleus. Keto et al. (1999) have shown that the IR peak contains a super star cluster (SSC) and have suggested that the radio nucleus is probably an AGN. Based on a high-resolution VLA image of the 15 GHz continuum emission, Turner & Ho (1985) discovered that the radio nucleus is an unresolved source with high brightness temperature and suggested that the nucleus could harbor an AGN. Multi-band tracers of ionized gas ([NeII]: Böker, Krabbe and Storey 1998; Keto et al. 1999; Bry : Forbes et al. 1993; optical continuum and line emission: Engelbracht et al. 1998; Watson et al. 1996; Forbes et al. 2000) show that the maximum emission at these wavebands coincides with the position of the IR peak.

NGC 253 is the second extragalactic object (outside the Magellanic Clouds) to have been detected in RRLs (H102 α line at 6.1 GHz at the Algonquin Radio Observatory; Seaquist & Bell 1977). This line emission was interpreted as arising due to stimulated emission from the thermal gas by the continuum emission of the galactic nucleus (Shaver, Churchwell & Walmsley, 1978). This interpretation was confirmed by Mebold et al. (1980) by modelling the H112 α line detected using the 100-m telescope at Effelsberg. The first interferometric observations of RRLs from NGC 253 were carried out by Anantharamaiah & Goss (1990), who imaged the H166 α , H110 α and the H92 α lines at 1.4 GHz, 4.8 GHz and 8.3 GHz respectively, using the VLA. The resolution of these observations is $\sim 35''$, $11''$ and $6''$ respectively. Modelling the higher frequency lines indicated that these lines arise in high density gas ($n_e \sim 10^4 \text{ cm}^{-3}$), mainly due to internal emission from compact HII regions. The H92 α line was observed by Anantharamaiah & Goss (1996) at a higher resolution of $\sim 1.3''$ (16 pc) and the kinematics of the ionized gas showed a distinct orthogonally rotating subsystem. The velocity field was later modelled in detail by Das, Anantharamaiah & Yun (2001) who explained the observations in terms of the motion of the gas in the gravitational potential of a bar. Puxley et al. (1997) observed mm-wave RRLs from this galaxy using the 45-m telescope of the Nobeyama Radio Observatory. They showed that the RRL flux density over a wide range of frequencies is consistent with a ν^2 law and hence suggested that the mm lines arise due to spontaneous emission from optically thin HII regions. They also derived a total ionization rate of $(3.7 \pm 0.8) \times 10^{53} \text{ s}^{-1}$, an order of magnitude higher than that derived from infrared emission lines.

Anantharamaiah & Goss (1990) model the low resolution H166 α line emission (beam size of $45'' \times 27''$) as arising from low density ($n_e \sim 100 \text{ cm}^{-3}$) gas. The location of this line emission is displaced from that of the 4.8 GHz and 8.3 GHz line emissions. We have observed NGC 253 at 1.4 GHz in order to image the H166 α line at a higher resolution. The properties of the ionized gas can be better constrained by determining the size of the line emitting region more accurately. Additionally, in order to check the reality of the position offset (Anantharamaiah, private communication), we have also reanalysed their C configuration data. Following the initial low resolution observations, the H92 α line was later imaged at a resolution of $1.8'' \times 1.0''$ by Anantharamaiah & Goss (1996). Two peaks of line emission were detected. The maximum of the line emission is coincident with the radio nucleus. The secondary line peak is offset by $\sim 3.5''$ SW from this position, and hence could possibly be the counterpart to the IR peak.

However, since the IR peak is believed to be the main site of star formation, RRL emission is not expected to peak towards the radio nucleus.

We have observed NGC 253 at 8.3 GHz and 15 GHz using the VLA in the A configuration with sub-arcsecond resolution. A number of pc-scale compact radio continuum sources exist in the central region where RRLs have been detected. Ulvestad & Antonucci (1997) have derived the spectral indices of these sources, which indicate significant amounts of thermal gas in some of these sources. Hence it is important to identify the individual continuum sources from which the line emission imaged at low resolution arises. As mentioned above, low resolution H 2α images indicate that the peak of the line emission coincides with the radio nucleus and this needs to be confirmed by high resolution observations. Modelling the line emission towards the nucleus can yield constraints on the gas properties in this region. Thus, the nature of the radio nucleus can be investigated.

3.2 Observations

In this section, we describe the 1.4 GHz RRL observations of NGC 253 and also the higher resolution observations of the line emission at 8.3 GHz and 15 GHz. Apart from the properties of the continuum and line emissions, the morphology of the high frequency line emission is also discussed in detail.

3.2.1 Observations at 1.4 GHz

NGC 253 was observed at 1.4 GHz using the VLA in the C as well as the BnA configurations in order to study the large scale recombination line emission at this frequency. The C configuration data, along with D configuration data, were used by Anantharamaiah & Goss (1990) to image the line emission at low resolutions. We have reanalysed the C configuration dataset here. Due to hardware problems during observations, about half the C configuration data were lost. Additionally, the amplitude of the visibilities in the inner uv plane ($uv < 0.5 \text{ k}\lambda$) exhibit spikes, possibly due to interference, and were hence discarded. Hence, the continuum imaging of the galaxy was affected by the problem of missing short spacings thus leading to the presence of extended negative features surrounding the central part of the galaxy. The rms noise was therefore twice that of the expected value. The well-known 3 MHz ripple was seen prominently in the bandshapes but could be well corrected due to frequent bandpass calibration. The time variation of the bandshapes was a few percent for the duration of the observation. However, since bandpass calibration was performed once every half hour, the time variation could be adequately corrected for, by interpolation.

Table 3.1: VLA observational log and image parameters

Parameter	1.4 GHz	1.4 GHz	8.3 GHz	15 GHz
VLA configuration	C	B	A	A
Date of observation	23/04/88	01/10/95	9/7 & 12/7 & 9/10/99	26/6/99
ν_{rest} of RRL (GHz)	1424.7 (H166 α)	1424.7(H166 α) 1374.6(H168 α)	8309.4 (H92 α)	15281.5 (H75 α)
Bandwidth (MHz)	3.03	3.03	24.2	46.9
# of channels, # IF	31, 4	31, 4	31, 1	15, 1
Spectral resolution ^a (km s ⁻¹)	41.1	41.1	56.4	122.6
Shortest baseline (k λ) ^b	1.5	2.4	7	12
Synthesized beam (″ $\times$ ″)	35 $\times$ 17	5.07 $\times$ 3.79	0.50 $\times$ 0.28	0.31 $\times$ 0.14
Phase calibrator	0023-263	0023-263	0116-219	0118-272
Bandpass calibrator	0023-263	0023-263,3C48	2251+158	2251+158
Peak continuum ^c (mJy/beam)	2000.0	675	40	37
Cont.m noise (1 σ , mJy/beam)	0.2	0.13	0.04	0.13
Noise per channel (mJy/beam)	—	0.26	0.12	0.35

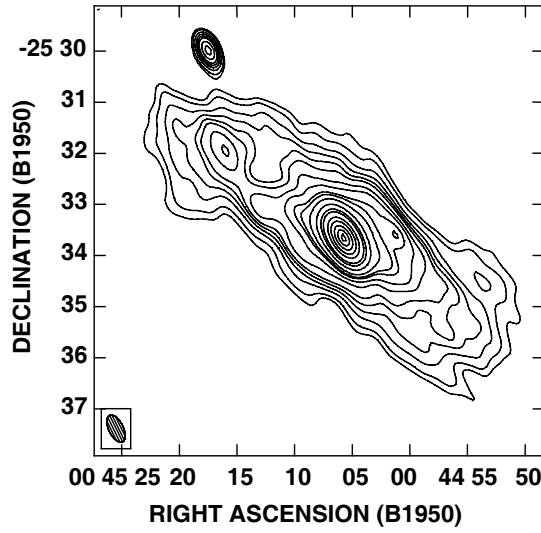
^aThe spectral resolution after off-line hanning smoothing.

^bShortest *well sampled* (in P.A.) baseline

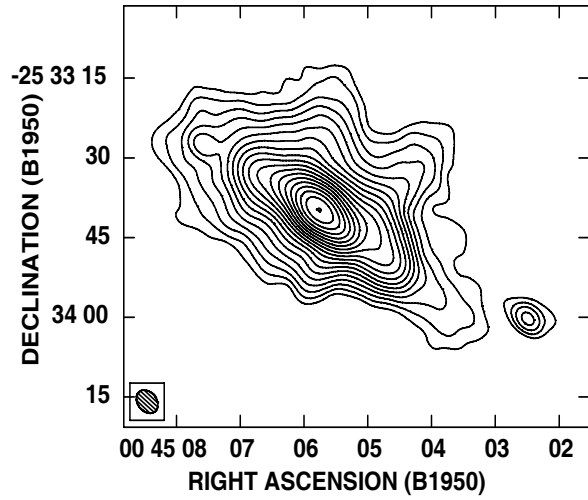
^cEvaluated by simultaneously fitting a gaussian, a zero level and a slope.

The continuum image of NGC 253 in the C configuration is shown in figure 3.1a. The 1.4 GHz recombination line was detected from the galaxy towards the centre. However, further inspection revealed problems in the dataset, for eg., temporal inconsistencies in the line emission and a sharp frequency gradient of the position of the peak line emission. Due to these reasons, we do not use the C array dataset to study the line emission. However, this dataset is used to image the continuum emission from NGC 253 at the highest sensitivity so far. Continuum sources are also detected in the resulting image at distances from the centre of the galaxy greater than what has been possible previously. The analysis of this continuum emission is presented in section 3.4.1. Anantharamaiah & Goss (1990) presented low resolution images of the RRL emission at 1.4 GHz, 4.8 GHz and 8.3 GHz using the VLA in the C and D configurations, with synthesized beam sizes of 22.7″ $\times$ 11.4″, 12.5″ $\times$ 8.8″ and 7.4″ $\times$ 5.2″ respectively. The line emissions at 4.8 GHz and 8.3 GHz were found to be centred on the peak of the continuum emission whereas the 1.4 GHz line emission was found to be shifted SE from the continuum peak and was hence modelled as a separate region of ionized gas. Subsequently, the D array data were found to be flawed due to bandpass problems (Anantharamaiah, private communication). Hence the positional offset between the 1.4 GHz and the higher frequency line emission presented by these authors is not real.

The B array observations were performed in the 4 IF mode of the correlator in order to detect both the H166 α (IF 1) and the H168 α (IF 2) lines. A number of strong sources lying within one primary beam of the galaxy were identified using the C configuration image. Multiple fields were defined around these sources and their emission was simultaneously deconvolved along with the central galactic emission. Bandwidth smearing was found not be significant; the degradation in the point source response 10′ away from the phase centre is about 3-4 %. Non-coplanarity of the array was also found to have a negligible influence and hence the inner 10′ region was imaged as a single field. Missing short spacings affect the BnA dataset as well, leading to negative bowls of emission in the image. The bandshapes were found to vary by a few percent during the time of observations but, as in the previous case, calibration every half



(a) 1.4 GHz continuum using C configuration

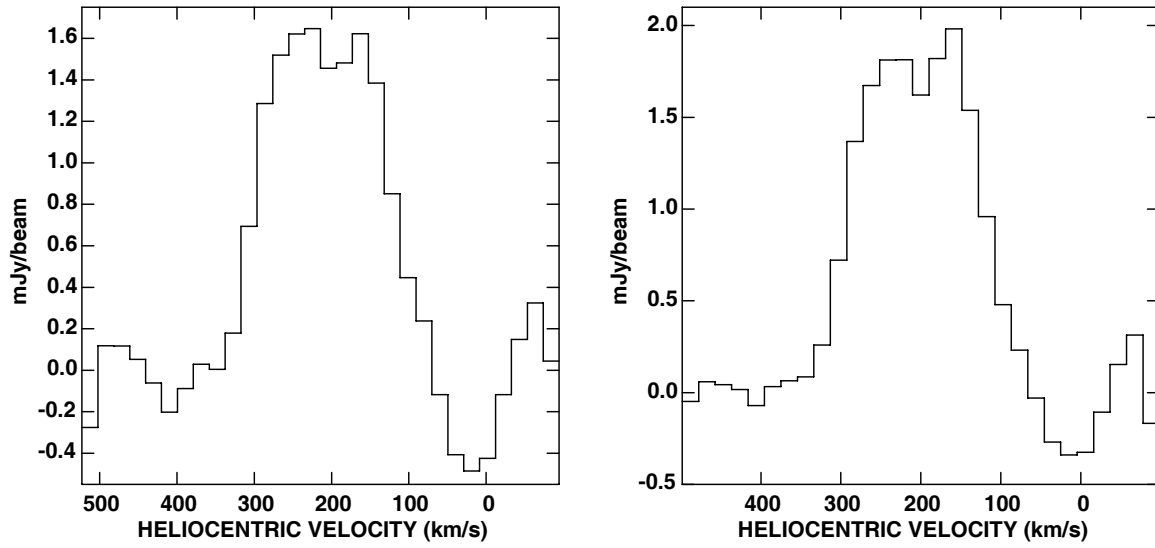


(b) 1.4 GHz continuum using B configuration

Figure 3.1: 1.4 GHz continuum emission from the inner disk of NGC 253 using the VLA in the **(a)**. C configuration. The rms in the image is 0.20 mJy/beam and the contour levels are in steps of (5, 10, 20, 30, 40, 50, 70, 90, 120, 140, 200, 400, 800, 1200, 2500, 4000, 6000, 8000, 9500) times the rms. The synthesized beam is $34.7'' \times 17.0''$ at a P.A. of 26° . **(b)**. B configuration. The rms in the image is 0.13 mJy/beam and the contour levels are from 1.3 mJy/beam to 664 mJy/beam in steps of $\sqrt{2}$. The synthesized beam is $5.1'' \times 3.8''$ at a P.A. of 51° .

hour proved adequate to track the time variation to much less than one percent.

The continuum image of the galaxy is shown in figure 3.1b. Both the H166 α and the H168 α lines were detected in the line cubes. The peak flux density, central velocity of the peak and the width of the H166 α line are consistent with that of H168 α line. The spectrum obtained from the combined dataset towards the continuum peak is shown in figure 3.2a. The peak line flux is ~ 1.6 mJy/beam. This line emission is marginally spatially resolved. To obtain a consistent estimate of the total line flux, we have reimaged the emission with a suitable taper such that the synthesized beam is as close to that of the H92 α observations of Anantharamaiah & Goss (1990) as possible. The resultant spectrum through the position of the peak of line emission is shown in figure 3.2b. The peak line emission in the tapered and untapered images are similar, which reflects the fact that the untapered image is only marginally resolved with no significant extended emission surrounding it. The line parameters are listed in table 3.7. The FWHM of the synthesized beam along the direction of the line of alignment of the compact continuum sources as well as that of the diffuse continuum emission is $5.0''$ - $5.3''$ in both the tapered and untapered images. In section 3.2.2, we present the image of the H92 α line emission at subarcsecond resolution. Based on this image as well as other low resolution images of line emission in NGC 253, it can be inferred that the synthesized beam covers all of the line emitting region. Therefore, based on the 1.4 GHz data, we cannot spatially resolve, and hence identify, the sites of line emission.



(a) 1.4 GHz RRL spectrum towards the continuum peak of B configuration image

(b) 1.4 GHz spectrum towards the continuum peak of tapered image

Figure 3.2: Co-added H166 α and H168 α spectra towards the continuum peak of NGC 253 using the B configuration data for (a). natural weighted image. Synthesized beam is 5.1'' $\times$ 3.8'' at a P.A. of 50° and the rms noise in the line cube is 0.26 mJy/beam. (b). image produced by tapering the visibilities and convolving the image such that the synthesized beam is 7.36'' $\times$ 5.20'' at a P.A. of -30°. The rms noise in the line cube is 0.27 mJy/beam.

3.2.2 Observations at 8.3 GHz and 15 GHz

The 8.3 GHz H92 α and the 15 GHz H75 α recombination lines from NGC 253 were observed using the VLA in the A configuration. This observing mode yields the required parsec-scale resolution with the best sensitivity possible. The datasets at 8.3 GHz were acquired over three periods. The datasets acquired on the first and third day exhibited bandshape problems, notably that due to the 3 MHz ripple. Hence the spectra towards various positions where line emission is seen were not consistent. The second day's dataset suffered from the least amount of bandpass problems. Hence, to study the weak extended emission, we use only the data taken on the second day. However, to study the line emission from the nucleus, which is much stronger compared to the typical ripple amplitude, we use the combined dataset. The parameters of the line emission towards the radio nucleus using the second days' data as well as the combined dataset are identical within errors. Continuum images were made at both 8.3 GHz and 15 GHz and are consistent with the images published by Ulvestad and Antonucci (1997); the flux densities of relatively isolated unresolved sources measured using our data agree with the values published by them to within 10 % with no significant systematic offsets.

The measured positions of the various features in the 8.3 GHz and 15 GHz continuum images do not coincide. In order to determine the global offsets, if any, in the two images, sources in the field which are unresolved and are relatively isolated and hence free of confusion from surrounding emission were selected. The images of the continuum emission from these individual sources at both frequencies were fit by a gaussian (whose width was constrained to be that of the CLEAN beam) and a tilted plane simultaneously, using the the AIPS task JMFIT. It

was found that the discrepancy in position between the images at the two frequencies can be explained by a global offset between the two images. The derived values of the positions were compared with the positions measured by Ulvestad & Antonucci (1997) from their A configuration 15 GHz image using the same method. The average offsets relative to the 15 GHz image of Ulvestad & Antonucci (1997) are $+0.036'' \pm 0.01''$ in R.A., $+0.14'' \pm 0.01''$ in Dec for the 8.3 GHz data and $+0.021'' \pm 0.007''$ in R.A. and $+0.012'' \pm 0.006''$ in Dec for the 15 GHz data. The largest offset seen is in declination for the 8.3 GHz data. These offsets are possibly due to positional uncertainties in the phase calibrators used. The continuum and line images at both frequencies were corrected for these offsets. The coordinates of the source 5.75-41.8 in the corrected images was found to be $00^h 45^m 05^s.751 -25^\circ 33' 41''.85$ (B1950.0) at 8.3 GHz and $00^h 45^m 05^s.750 -25^\circ 33' 41''.86$ (B1950.0) at 15 GHz. The images of radio continuum emission at the two frequencies are shown in figure 3.3 and figure 3.4. Note that, due to this global correction applied to the coordinates of the 8.3 GHz and 15 GHz emissions, absolute positional information is lost. Hence, all positions quoted for individual sources in this chapter are with reference to the position of the radio nucleus, mentioned above.

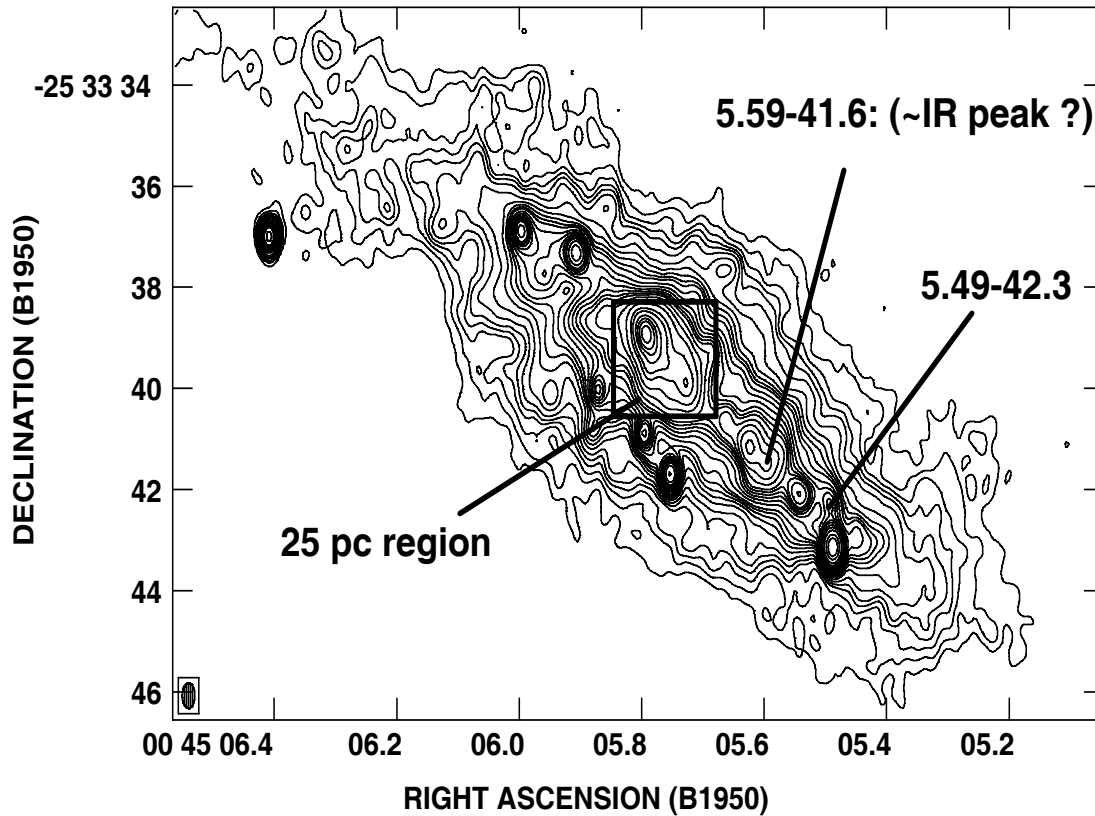


Figure 3.3: Continuum emission at 8.3 GHz from the central disk of NGC 253 using the VLA in the A configuration. Data from all three days have been combined. The rms in the image is $40 \mu\text{Jy/beam}$ and the peak flux is 63.1 mJy/beam . The contour levels are (4, 6, 8, 10, 12, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 90, 100, 120, 150, 200, 300, 400, 600, 800, 1000, 1300) times the rms. The synthesized beam is $0.50'' \times 0.28''$ at a P.A. of 0° .

We use the data from the second day's observations at 8.3 GHz to study the global $\text{H}2\alpha$

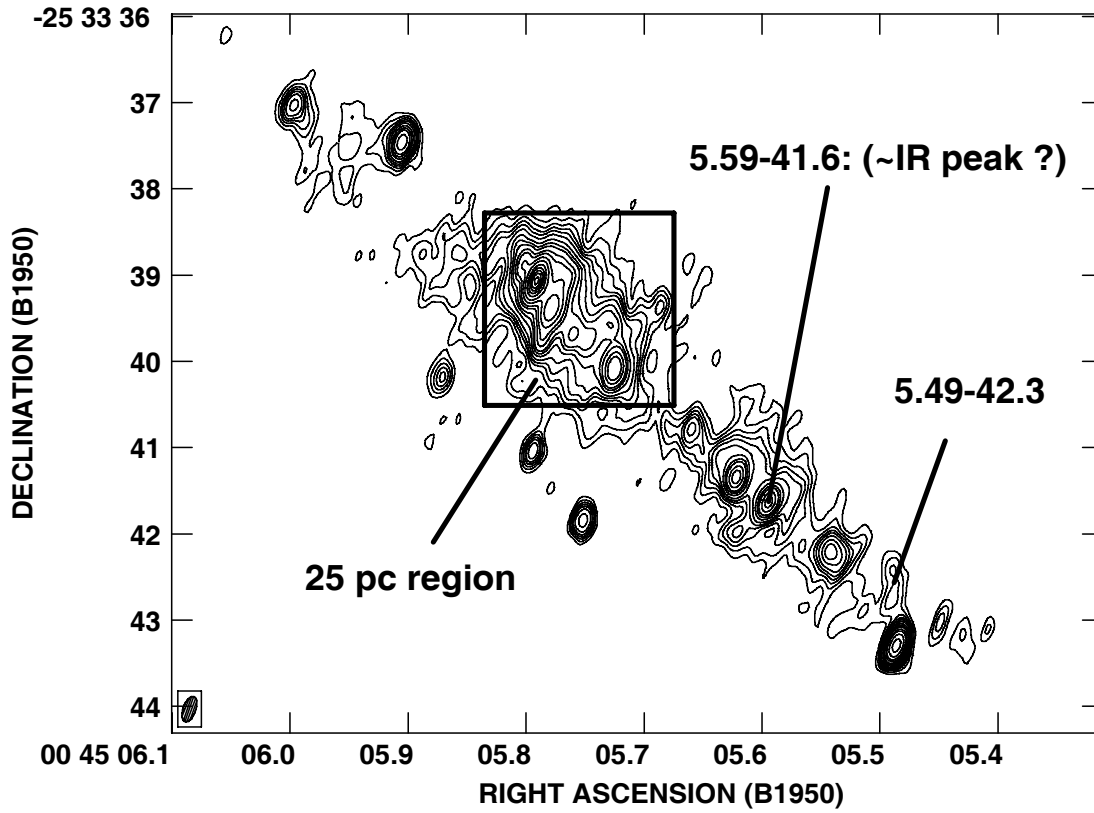
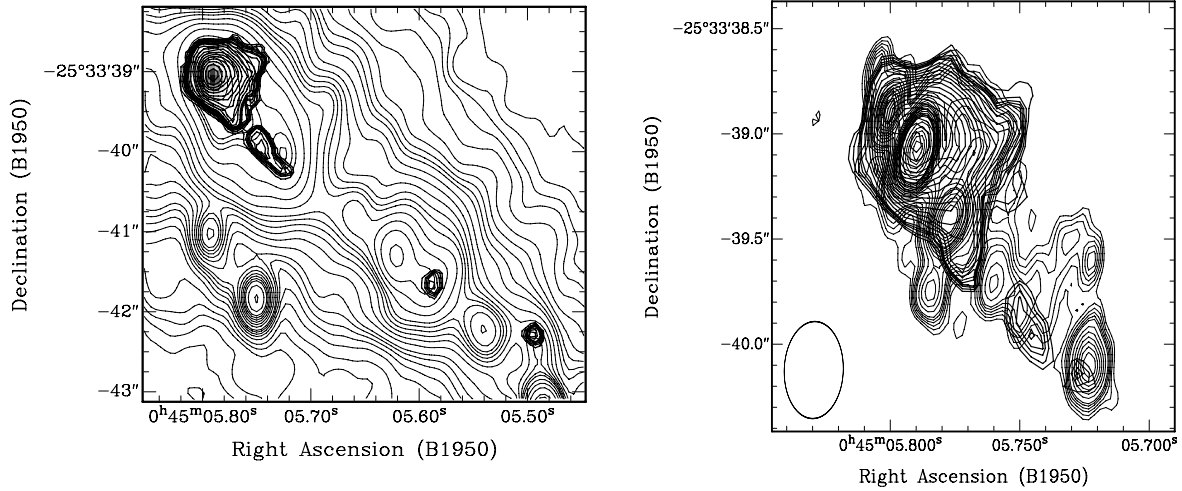


Figure 3.4: Continuum emission at 15 GHz from the central disk of NGC 253 using the VLA in the A configuration. Data from both days have been combined. The rms in the image is $120\mu\text{Jy}/\text{beam}$ and the peak flux is $44.1\text{ mJy}/\text{beam}$. The contour levels are (4, 6, 8, 10, 12, 15, 20, 25, 30, 40, 50, 70, 100, 150, 200, 250, 300, 350) times the rms. The synthesized beam is $0.31'' \times 0.14''$ at a P.A. of -20° .

line emission. The rms of the noise in the line cube is $0.12\text{ mJy}/\text{beam}$ in the channels containing line emission. The line emission is seen predominantly from the central 25 pc sized region of the galaxy. Spectra towards the peaks of continuum emission from each of the compact sources seen in figures 3.3 and 3.4 were inspected for significant line emission. Sources of line emission thus identified were also visible in the image of the integrated line emission. A lower resolution line cube was constructed by applying a gaussian taper of $200\text{ k}\lambda$ (which is the uv distance where the gaussian reached 30 % of its maximum value) to the visibilities, with a resulting synthesized beam of $1.1'' \times 0.8''$. The resulting image of the integrated line emission also clearly delineates the prominent line emitting regions identified from the untapered images. The integrated $\text{H}92\alpha$ emission image using the full resolution dataset is shown in figure 3.5a overlaid on an image of the continuum emission from the region. Two compact sources and an central extended region of line emission can be seen. The western most source is almost coincident with a continuum source which is just about resolved from a stronger southern compact object. This continuum source is named 5.49-42.3 by Ulvestad & Antonucci (1997) and is also identified by them as a thermal source. Hence we associate the line emission with 5.49-42.3. The other compact line emitting region $1.5''$ east of the first source is displaced $\sim 0.06\text{--}0.1''$ southwest of the compact continuum source 5.59-41.6. This is the radio continuum source closest to, though not exactly

coincident with, the prominent IR peak. Hence we tentatively identify this RRL source with the IR peak. The reality of this association is discussed in detail in section 3.4.3.2. The eastern most $\sim 2''$ sized extended region, marked as the "25 pc region" in figures 3.3 and 3.4 is host to most of the RRL emission seen at this frequency.



(a) Integrated H92 α emission overlaid on 8.3 GHz continuum emission

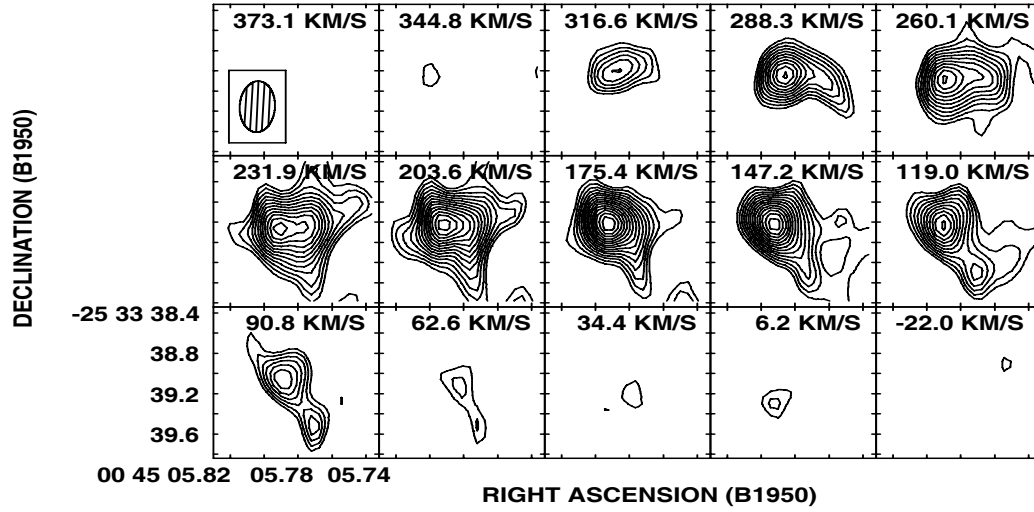
(b) Integrated H92 α emission of the inner '25 pc region' overlaid on high resolution 15 GHz continuum emission

Figure 3.5: **(a).** The H92 α line emission, shown by thick contours, overlaid on the 8.3 GHz continuum emission, shown as thin contours. The image parameters are the same as in figure 3.3. Two compact sources of line emission can be seen towards the west, and the extended emission, split in two components, can be seen within the '25 pc region' towards the east of the image centre. **(b).** A close-up view of the H92 α line emission towards the 25 pc region, shown as thick contours, overlaid on a high resolution 15 GHz continuum image. The line emission can be seen to consist of two additional compact sources as well as a contiguous central line emitting region. The latter will be referred to as the '15 pc region'.

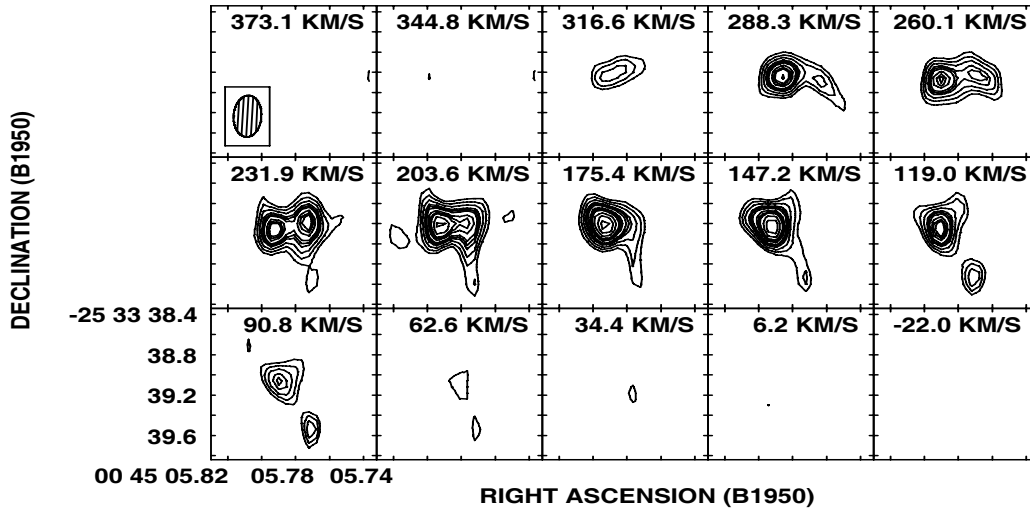
Anantharamaiah & Goss (1996) imaged the H92 α line emission in this galaxy at much lower resolution using the VLA in the B configuration and found that almost all the line emission arises in two regions. The strongest peak coincides with the nuclear region and the second is close to the position of the IR peak. Higher resolution A configuration data presented here resolves the former emission, spread over $\sim 2''$, into a number of distinct line emitting regions. The integrated line emission from this '25 pc region' is shown in figure 3.5b overlaid on the 15 GHz continuum emission. This continuum emission is imaged at the highest possible resolution (by 'uniformly' weighting the visibilities) in order to resolve the individual compact sources. Two distinct spatially resolved regions of line emission are seen southwest of the nuclear region. The westernmost line emitting region is close to the continuum source 5.72–40.1. The more eastern of the pair of line emitting regions cannot be readily identified with a particular continuum source. The continuum source closest to the line emission, though not necessarily associated with it, is 5.75–39.9. The dominant line emission, however, arises in an extended region northeast of the pair of compact sources and has a size of $\sim 1.2''$ (~ 15 pc). The peak of

this line emission coincides with that of the radio nucleus. The extensions in the western and southwestern direction from the nucleus can be resolved into three additional sources in higher resolution line images. Shown in figures 3.6 are the channel maps of the line emission in the velocity range 373.1 km s^{-1} to -22 km s^{-1} . The images in figure 3.6a have the highest possible sensitivity since they are made with ‘natural’ weights to the visibilities. The synthesized beam is $0.51'' \times 0.28''$. Figure 3.6b also shows the 8.3 GHz channel images, but at a higher resolution of $0.41'' \times 0.22''$, though at the expense of a negligible decrease in sensitivity by a factor 1.1. This was achieved by using a value of the ‘robustness’ parameter (Briggs, 1999) of 0.5. As mentioned above, this line emitting region is composed of at least four sources. These are only marginally resolved in most of the channel images of the natural weighted image whereas they can be seen to be more clearly resolved in some of the higher resolution images. It is not immediately apparent whether the entire emission seen over the $\sim 1.2''$ can be fully decomposed into at most four compact sources which are presumably spatially unresolved and this issue is discussed in detail in section 3.4.2. The H92 α spectra towards the four distinct line sources outside the $1.2''$ sized central region are presented in figure 3.7. Figure 3.8 shows the spectrum towards the extended central ‘15 pc region’, where the line emission has been added over pixels whose intensity is at least 2σ .

In summary, the H92 α line emission has been imaged at a resolution of $\sim 0.4''$. The morphology of the integrated emission is seen to consist of two compact sources west of the nuclear region and a 25 pc sized region of extended emission. This 25 pc sized region contains two more compact sources of line emission as well as a contiguous extended line emitting region, referred to as the ‘15 pc region’. This 15 pc sized line emission, in turn, can be decomposed into four more compact line emitting sources.



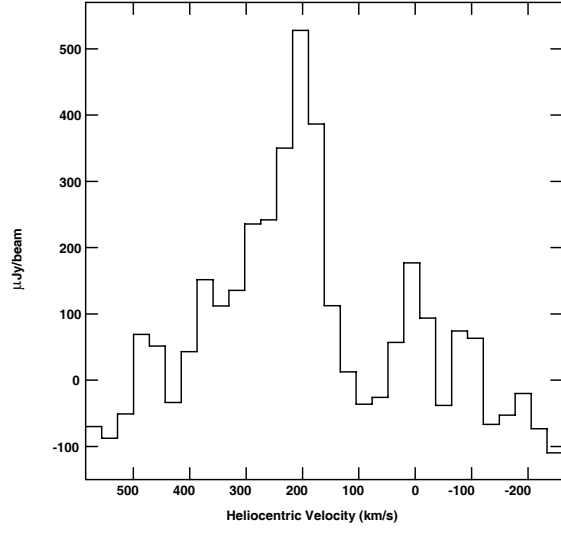
(a) 8.3 GHz channel images



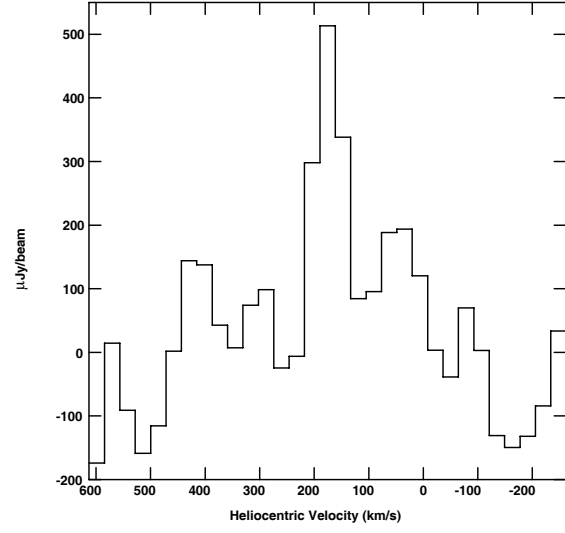
(b) 8.3 GHz channel images at higher resolution

Figure 3.6: VLA A configuration images of the H92 α line emission in individual spectral channels (channels 9 to 23) in the central ‘25 pc region’ of NGC 253. The central heliocentric velocity of each channel is marked in km s^{-1} at the top of each frame. Line emission only in every alternate channel is independent due to off-line hanning smoothing. **(a).** Line images at low resolution and high sensitivity using natural weighting of the visibilities. The synthesized beam is $0.50'' \times 0.28''$ and the rms in the channel images is 0.12 mJy/beam. The contour levels are (3.5, 4, 4.5, 5, 5.5, 6, 7, 8, 9, 10, 11) times the rms. **(b).** Line images at higher resolution and slightly lower sensitivity using robust weighting of the visibilities. The synthesized beam is $0.41'' \times 0.22''$ and the rms in the channel images is 0.13 mJy/beam. The contour levels are (3, 3.5, 4, 4.5, 4.75, 5, 5.5, 5.8, 6, 6.5, 7, 7.5) times the rms.

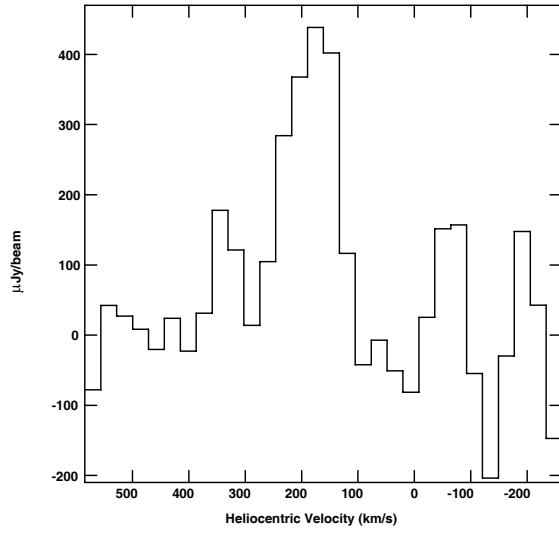
The 15 GHz line cube was used to search for the H75 α line from NGC 253. The rms noise in the channel images is 0.36 mJy/beam. The peak of the H75 α emission is coincident with the radio nucleus (the peak of a fitted gaussian is displaced one pixel from the position of the continuum peak, which we attribute to the effects of low signal to noise). Surprisingly, the only other source of RRL emission arises from a compact source about 0.35'' northwest of the nucleus. This source seems to have corresponding H92 α line emission at 8.3 GHz, associated with the continuum source 5.76–39.9, and is the strongest line emitting source at the latter frequency barring the radio nucleus. The channel images of the H75 α line emission as well the H75 α spectra towards the two sources are shown in figure 3.9.



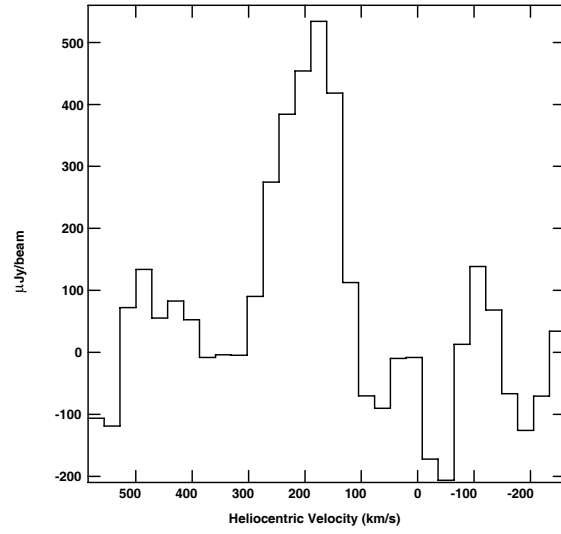
(a) H92 α spectrum towards 5.49–42.3



(b) H92 α spectrum towards 5.59–41.6



(c) H92 α spectrum towards 5.72–40.1



(d) H92 α spectrum towards 5.75–39.9

Figure 3.7: H92 α spectrum towards the four compact line emitting sources outside the 15 pc region in NGC 253 using the VLA in the A configuration, indicated by the names of the continuum sources which are most probable associations: **(a).** 5.49–42.3, **(b).** 5.59–41.6, **(c).** 5.72–40.1 and **(d).** 5.75–39.9. The synthesized beam is $0.50'' \times 0.28''$. The rms in the line cubes is 0.12 mJy/beam and the velocity resolution is 56.4 km s^{-1} .

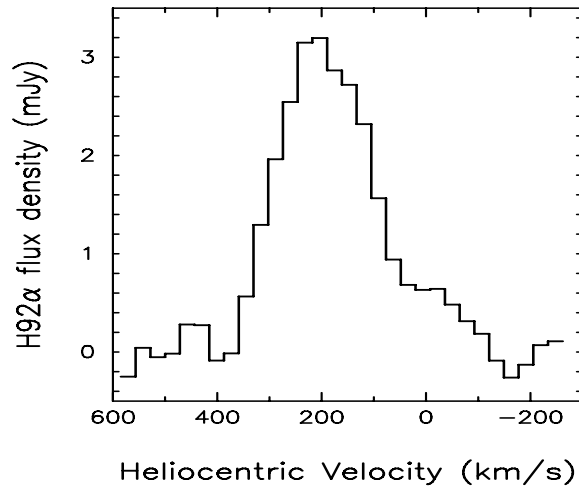


Figure 3.8: The H92 α line spectrum integrated over the 15 pc region. The area of integration includes all points whose line intensity is greater than 2σ .

As was mentioned earlier, the high resolution H92 α and H75 α lines peak towards the radio nucleus, whose nature is still not well understood. Therefore we first discuss, in the following section, the RRL emission towards the unresolved nucleus and attempt to deduce the nature of the radio nucleus. Following this, we discuss the surrounding extended emission in section 3.4.

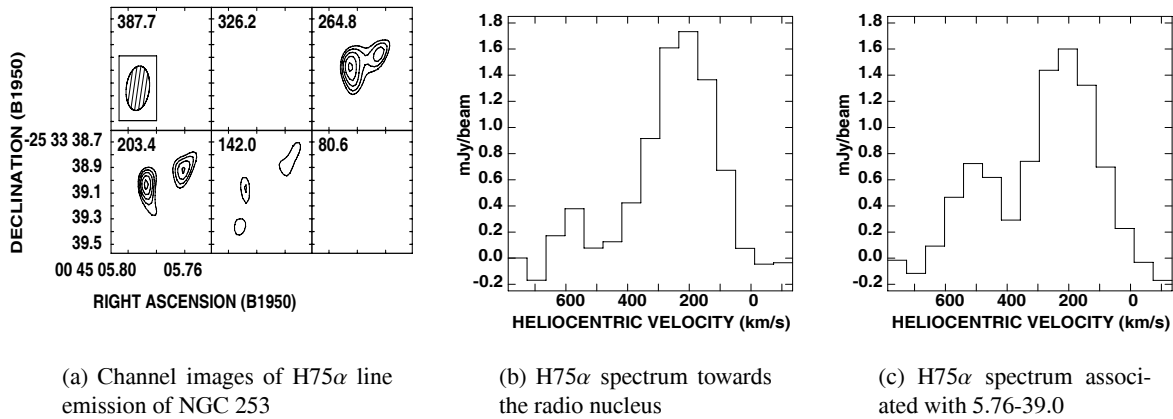


Figure 3.9: **(a).** VLA A configuration ‘naturally weighted’ images of H75 α emission in individual channels (channel 7 to 12) from the central ‘25 pc region’ of NGC 253. The central heliocentric velocity of each channel is marked in km s⁻¹ at the top left corner of each frame. Emission in every alternate channel is independent due to off-line hanning smoothing. The synthesized beam is $0.35'' \times 0.22''$ and the rms in the channel images is 0.36 mJy/beam. The contour levels are (3.5, 3.8, 4.1, 4.4, 4.7, 5, 5.3) times the rms. **(b).** H75 α spectrum towards the peak of the nuclear continuum emission, or the radio nucleus. **(c).** H75 α spectrum towards the second line source 5.76-39.0.

3.3 The radio nucleus

The continuum image of NGC 253 shows that the central few arcseconds consists of a number of compact sources embedded in diffuse emission, and a few of these sources are spatially resolved at 23 GHz. Most of these sources are predominantly non-thermal, and some have a significant fraction of thermal gas in them. The peak of the continuum emission corresponds to the radio nucleus and is associated with the source 5.79-39.0 in the compact source catalog of Ulvestad and Antonucci (1997). Though the central 3'' region contains multiple sources, the nucleus is separable from the surrounding emission with our resolution of 0.3''. This radio nucleus is a rather special source, since its nature is still not completely known. Since the recombination lines at both 8.3 GHz and 15 GHz are seen to peak towards this source, we investigate the line emission towards the radio nucleus separately, in this section.

The radio nucleus is spatially unresolved even at 23 GHz (Ulvestad & Antonucci, 1997). Though the H92 α emission peaks towards the nucleus, it is surrounded by extended line emission. Therefore, in order to compare the continuum and line data at the two frequencies, we convolve the images at 8.3 GHz and 15 GHz to a common resolution of 0.35'' $\times$ 0.22'' at a P.A. of -10° . The image parameters for the radio nucleus corresponding to a single synthesized beam area are listed in table 3.2.

Table 3.2: Input parameters for RRL models of the radio nucleus

Parameter	8.3 GHz data	15 GHz data
Peak continuum flux density ^a (mJy/beam)	40	37
Peak line flux density (mJy/beam)	0.92 $\pm$ 0.02	1.72 $\pm$ 0.02
Integrated flux ^b ($\times 10^{-23}$ W/m ²)	6 $\pm$ 1	23 $\pm$ 2
FWHM of line ^c (km s ⁻¹)	225 $\pm$ 15	197 $\pm$ 26
Noise per channel (mJy/beam)	0.14	0.35

^aEvaluated by simultaneously fitting a gaussian, a zero level and a slope.

^bCorresponding to the spectrum against the unresolved radio nucleus.

^cThe FWHM after deconvolving the effects of hanning smoothing and finite spectral resolution.

3.3.1 Modelling the ionized gas

The properties of the ionized gas within the radio nucleus were modelled using the observed continuum and recombination lines at 8.3 GHz and 15 GHz (see table 3.2). These observational constraints correspond to an area of ~ 4 pc (one synthesized beam). The results of Models I, II and III (which correspond to a single spherical HII region, an uniform slab and a collection of HII regions respectively) are very similar and hence we will only discuss the spherical HII region model (Model I). The relative locations of both the line emitting thermal gas and the non-thermal continuum source along the line of sight within the synthesized beam are unknown. Hence, the fraction of the non-thermal continuum radiation which is behind the thermal gas (and is responsible for the stimulated line emission) is varied from zero to the total observed continuum flux density in the models. For every combination of n_e , l and T_e , the continuum and line flux densities were then calculated. Of these combinations, those models which reproduce the observed line emission at both frequencies and also predict continuum flux densities consistent with the observed values were accepted as valid solutions. The details of the modelling

procedure are described in section 2.3.

Table 3.3: RRL model details (spherical geometry)

Parameter	Range
<i>Explored input parameter space</i>	
Electron temperature (T_e , K)	2500–12500
Local electron density (n_e , cm^{-3})	10^{-2} – 10^6
Diameter (l , pc)	0.01–5.0
<i>Model solutions for $T_e=5000$–12500 K</i>	
n_e (cm^{-3})	6000–17000
l (pc)	2–5.0
N_{Lyc} (s^{-1})	$(6-20) \times 10^{51}$
M_{HII} ($M_\odot$)	1000–7000
Stimulated emission (at 15 GHz, %)	10–60
Thermal continuum fraction (15 GHz)	0.15–0.7

The range of values for various solutions are indicated in table 3.3. The results do not depend sensitively on the assumed value of the electron temperature within the range explored, and hence $T_e=5000$ – 7500 K is assumed. No solutions were obtained if the gas is assumed to be in LTE; the linear size of the region is too small and the background non-thermal radiation is too weak to produce a detectable RRL. Hence line enhancement due to non-LTE processes is essential to explain the observed line flux. Only a narrow range of densities (6×10^3 – $1.7 \times 10^4 \text{ cm}^{-3}$) is allowed and the ionizing photon rate ranges from $(6-20) \times 10^{51} \text{ photons s}^{-1}$. The predicted continuum and line emissions for typical solutions are shown in figure 3.10. The properties of the ionized gas are also derived using the multi-density model (Model IV). In this model, gas at densities very different from the values derived above (see table 3.3) does not contribute significantly to the observed RRL emission (see section 2.3.2). Hence the constant density approximation used in the above models is justified. For values of $n_e < 6 \times 10^3 \text{ cm}^{-3}$, the computed line emissions inside a ~ 4 pc region fall short of the observed values, with the discrepancy being larger for smaller densities. For $n_e > 1.7 \times 10^4 \text{ cm}^{-3}$, the model predictions do not agree with the observed $\text{H}92\alpha/\text{H}75\alpha$ line ratio. Internal emission alone can explain the observations without the need for stimulated emission by a background continuum. For a given emission measure, stimulated emission enhances the recombination line emission compared with the value for pure spontaneous emission. Hence, the mass of ionized gas needed and the required ionizing photon flux are both less by a factor 2-3 for models incorporating non-thermal continuum radiation. If the entire observed continuum is assumed to be a distributed uniform background, then stimulated emission can account for up to 60–70 % of the total $\text{H}75\alpha$ line emission.

If these models are computed for either the $\text{H}92\alpha$ or the $\text{H}75\alpha$ line alone, the density range obtained is 10^3 – $2.5 \times 10^4 \text{ cm}^{-3}$. The ionization requirements are similar to the two-line models, with a minimum N_{Lyc} of $\sim 2.5 \times 10^{51} \text{ s}^{-1}$. Hence the assumption that the same gas is responsible for both observed RRLs is reasonable. Thus the observed $\text{H}75\alpha$ and $\text{H}92\alpha$ lines arise in gas with a mass of a few thousand $M_\odot$, a density of $\sim 10^4 \text{ cm}^{-3}$ and require an ionizing photon flux of $\geq 6 \times 10^{51} \text{ s}^{-1}$.

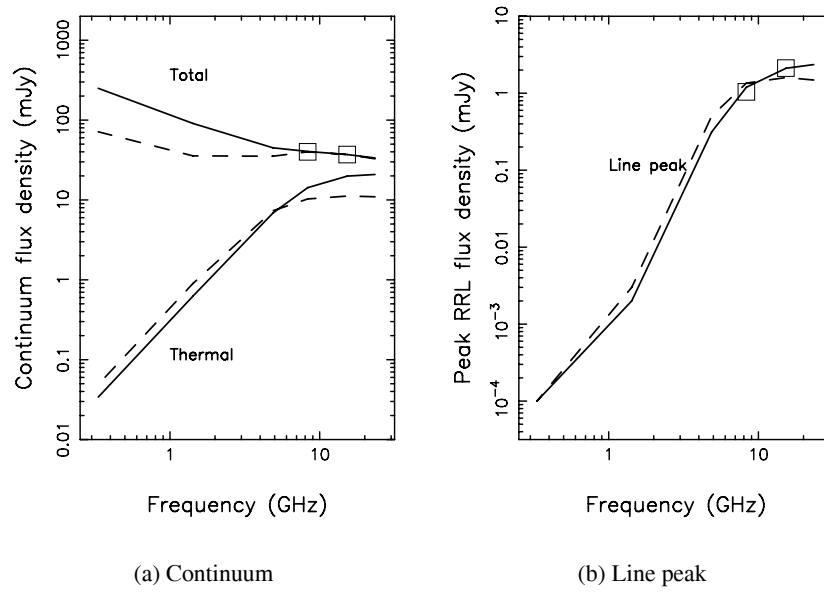


Figure 3.10: Predicted thermal continuum, total continuum and peak recombination line emission as a function of frequency for particular models of the radio nucleus. The solid line corresponds to a single spherical HII region model (Model I) where the non-thermal continuum is assumed to be in front of the thermal gas, with a spectral index of -0.7 . The specific model plotted is for $n_e=10^4 \text{ cm}^{-3}$, $l=3.26 \text{ pc}$ and $T_e=7500 \text{ K}$. The dashed lines correspond to a collection of HII region model (Model III) where the thermal gas is assumed to be in front of the non-thermal continuum with a covering factor of unity, The specific model plotted is for $n_e=10^4 \text{ cm}^{-3}$, $l=1.13 \text{ pc}$, $N=12$, $B=5 \text{ pc}$ and $T_e=7500 \text{ K}$. The square symbols indicate the measured values.

Table 3.4: Typical model results : for a spherical geometry with $T_e=7500 \text{ K}$.

Parameter	$n_e=7 \times 10^3 \text{ cm}^{-3}$			$n_e=1.7 \times 10^4 \text{ cm}^{-3}$		
	A ^a	B	C	A	B	C
Diameter l (pc)	3.1	4.0	3.5	2.1	2.3	2.1
$N_{\text{Lyc}} (\times 10^{52} \text{ s}^{-1})$	0.8	1.6	1.0	1.4	1.9	1.4
$S_{\text{th}}/S_{\text{total}}$ at 15 GHz	0.3	0.6	0.4	0.4	0.5	0.4
Stimulated emission ^b (%)	55	0	—	22	0	—
Spectral index ^c ($S_\nu \propto \nu^{-\alpha}$)	0.45	0.5	0.45	0.7	0.75	0.7
$M_{\text{HII}} (\times 10^3 M_\odot)$	2.8	6.0	3.7	2.1	2.8	2.2

^a A, B, and C refer to models where the non-thermal continuum is assumed to be behind, in front of, and mixed with, the ionized

gas.

^b The fraction of H75 α line emission due to stimulated emission by the background radiation.

^c Average spectral index of the de-absorbed continuum radiation, excluding the thermal contribution of the ionized gas.

3.3.2 Ionizing source

The RRL detection from the unresolved radio nucleus is from a sufficiently small linear size that the interpretation is not complicated by the unknown beam filling factors of the gas. The derived ionizing photon flux inside a $\sim 0.3''$ (4 pc) region can be compared with the values computed from other tracers of ionized gas. Using photo-ionization models, the derived ionization rate

of $6 \times 10^{51} \text{ s}^{-1}$ corresponds to a $H\alpha$ flux of $1.2 \times 10^{-14} \text{ W/m}^2$. Almost all measurements of line fluxes available in the literature ($H\alpha$, $\text{Br}\gamma$, $[\text{NeII}]$) correspond to significantly larger apertures and hence a direct comparison is difficult. Forbes et al (2000) list the $H\alpha$ fluxes of compact optical sources measured inside a $0.4''$ aperture. Since the strength of the line emission at the position of the radio nucleus is weak (Watson et al. 1996 and Forbes, private communication), we can assume that the $H\alpha$ flux from this area is less than that of the weakest source listed in their table. Then the extinction derived using the $H\alpha$ flux estimated from RRL modelling is $A_V > 14$, consistent with the $A_V = 24 \pm 6$ derived by Sams et al. (1994) towards the radio nucleus.

Since the region of interest is highly obscured, the source of the photo-ionization remains uncertain. We have considered three possible candidates : (1) supernova remnant expanding in a dense medium, (2) stellar cluster and (3) AGN. Each of these will now be examined in detail to investigate which of these can explain the observed properties of the nuclear region. The imposed constraints are the derived properties of the ionized gas, namely, the gas density, size, ionizing flux and line width and also the radio, UV (derived from ionization) and X-ray luminosities of the nucleus. The 2–10 keV luminosity (L_{2-10}) of the X-ray source coincident with the radio nucleus is $7 \times 10^{38} \text{ ergs s}^{-1}$ (unresolved for $E > 2 \text{ keV}$; Pietsch et al. 2001, using the *XMM-NEWTON*). The dynamical age of the gas ($\sim \text{radius/velocity}$) is calculated to be $\sim 10^4$ years and the sound crossing time ($\sim \text{radius/sound speed}$) is $\sim 10^5$ years. The small dynamical age coupled with a large ionization requirement is what makes this RRL detection interesting. Together, these impose strong constraints on the nature of the ionising source. It is to be noted that due to heavy extinction, the velocity dispersion of the gas within the radio nucleus is inaccessible to any other tool other than radio lines.

3.3.2.1 A compact SNR as an ionizing source

In this section, we consider the nucleus to host a compact supernova remnant (SNR) expanding into a dense ambient medium. The high ambient density slows down the expansion and also provides a high pressure environment. Hence compared to a normal SNR of the same age, a compact SNR would be smaller in size and expand slower as well. If the observed line width is attributed to the expansion velocity, this factor could explain both the wide lines and the small size of the line emitting region. The high ambient density also causes the SNR to transit from the Sedov-Taylor phase to the radiative, or snowplough phase, sooner than an SNR in a lower density medium. In the latter phase, the swept-up gas cools and forms a thin shell, which can be ionized by the X-ray photons from the hot gas inside the remnant. The observed RRLs would then arise from this ionized gas. This model was invoked by Chevalier and Fransson (2001) to explain some of the compact radio sources in the starburst galaxy M 82 and in Arp 220 as well. The Σ -D relation for SNRs in M 82 predicts that the brightness temperature T_B of a remnant of diameter $\leq 1 \text{ pc}$ will be greater than $\sim 10^5 \text{ K}$. Though the scatter in this relation is large, this estimate is consistent with the derived lower limit to the value of T_B for the nucleus of NGC 253.

In our model, the input parameters are the initial energy of the explosion, E_0 , the ambient density, n_0 , and the age of the compact SNR. Following the work of Draine and Woods (1991), we calculate the velocity and radius of the shock front as a function of time, E_0 and n_0 by numerically integrating the well known dynamical equation for different phases of expansion and follow the remnant for up to five million years. The transition from Sedov phase to the

snowplow phase is assumed to happen when the radiated energy up to that time equals 35 % of the initial energy E_0 . The density of the ionized gas downstream of the shock is given by $n_{\text{HII}}(t) = n_0 V_s^2(t)/c_i^2$ where $V_s^2(t)$ is the shock velocity at time t and c_i is the sound speed in the ionized medium. The time dependent 2–10 keV X-ray luminosity was also computed as a function of time. For the Sedov phase, the similarity solutions given in Newman (1977) and Landau & Lifshitz (1959) were used. For the radiative phase, the 2–10 keV luminosity was computed as the sum of the two components : from the rapidly cooling gas just behind the shock front at a temperature T_s and from the hot gas interior to the shock front at a temperature $T > T_s$. The latter is approximated to be at a constant density inside the remnant and assumed to cool mainly due to adiabatic losses with negligible heat conduction. The contribution to the X-ray luminosity from line emission and from gas at $T < T_s$ is neglected. The relevant expressions derived for the X-ray luminosity as a function of time and frequency are not given here.

In this model, the width of the RRLs is attributed to the expansion velocity of the SNR. Hence the shock front is required to expand at a speed $\sim 100 \text{ km s}^{-1}$ when it is a few pc in size. This is achievable in the model only if the ambient density is greater than about 10^3 cm^{-3} . Since the RRL emitting gas needs to have cooled sufficiently so as to recombine, this gas must be a part of the thin shell behind the shock front, which is formed during the radiative phase of the SNR. That is, since we observe RRLs from this source, the SNR must now be in the radiative phase. Hence we have explored the input parameter space for a solution such that the radius and velocity of the shock front, and the 2–10 keV luminosity for the SNR in the radiative phase matches the observational constraints. However, an additional condition exists. RRL models constrain the density of the RRL emitting gas to be about 10^4 cm^{-3} . Since this gas is assumed to be in a thin radiative shell, its density is given by $n_0 \times (V_s/C_i)^2$. Since the observed value of $(V_s/C_s)^2$ is about 10^2 , this implies that n_0 should be about 10^2 cm^{-3} . For this value of n_0 , our models do not give solutions consistent with the constraints imposed and hence, in this model, the observations and the derived properties cannot be explained. It should be noted that the other two constraints, namely the ionization and the mass of the ionized gas (assumed to be equal to the swept-up mass), can indeed be satisfied by the model, along with the 2-10 keV luminosity constraint. In conclusion, the properties of the nucleus cannot be explained by an SNR expanding in a dense medium.

3.3.2.2 A star cluster as an ionizing source

In this section, we assume that the nucleus hosts a stellar cluster and derive its properties. The number of O stars necessary to produce $> 6 \times 10^{51}$ photons s^{-1} is > 450 and the total mass of the cluster is $> 8.5 \times 10^4 M_\odot$ (computed assuming a Salpeter IMF with a mass range between 1–80 $M_\odot$ and using the tables in Vacca, Garmany and Shull 1996). Since the region modeled is ~ 4 pc in extent, the resultant total stellar mass and the lower limit to the stellar surface density imply that the ionizing source must be a Super Star Cluster (SSC; Meurer et al 1995). The RRLs are assumed to arise in the HII region formed around this SSC (similar to ‘supernebulae’ or UltraDense HII regions discovered in centres of other galaxies: Kobulnicky and Johnson 1999; Neff and Ulvestad 2000; Tarchi et al. 2000; Turner, Beck and Ho 2000; Mohan et al. 2001). The detection of wide lines with FWHM of $\sim 200 \text{ km s}^{-1}$ from within a ~ 4 pc region is a constraint on the dynamics of the nebula, which we investigate below.

Though a HII region ionized by a central cluster will expand outwards due to thermal over-

pressure, its expansion velocity can never exceed the speed of sound in the ionized medium (Spitzer 1968) and hence cannot account for the wide lines observed. Faster flows are observed in champagne flows, where a sharp enough density gradient in one direction leads to larger expansion speeds in that direction. However, champagne flows in HII regions cannot produce velocities larger than $\sim 50 \text{ km s}^{-1}$ (Yorke, Tenorio-Tagle and Bodenheimer 1984). Though supersonic velocities are known in extragalactic HII regions, their line widths are only $\sim 30\text{--}100 \text{ km s}^{-1}$ and the HII regions which exhibit this behaviour are also much larger in size (for eg., Muñoz-Tuñón, Tenorio-Tagle and Casteñada 1996). Note that the origin of these supersonic velocities is still unknown. The only plausible way to explain the observed velocity width is by invoking a stellar-wind driven HII region expanding at $\sim 100 \text{ km s}^{-1}$ into the ambient medium. The expansion velocity of a wind-driven shell scales as $(L_{\text{mech}})^{1/5}$ (Dyson & Williams, 1997), where L_{mech} is the mechanical luminosity of the wind. Hence an expansion velocity of 100 km s^{-1} for a cluster whose L_{mech} is $\sim 10^3$ times that of an O star is easily obtainable, based on the properties of galactic Wolf-Rayet wind driven bubbles. The dynamical age of a wind-driven shell is $\sim 0.55 \times R_{\text{shell}}/V_{\text{shell}}$ (McCray 1983), i.e., $\sim 10^4$ years. The dynamics is modelled in detail below, taking into account all of the observational constraints.

The model considered here is that of a uniform density nebula whose dynamics is determined by the ionizing photons and the stellar wind of a central SSC. In the wind-driven phase of expansion, the nebula quickly enters the snowplow phase ($\leq 10^3$ years), wherein it can be either in the energy-conserving or in the momentum-conserving phase. In the snowplow phase, since the density compression can be much larger than 4, the swept-up matter forms a thin shell which we assume can trap all of the ionizing photons emitted by the central cluster. The input parameters are the star formation history of the cluster, the constant ambient density (n_0) and the age of the cluster (assumed to be the same as the nebula) and the range of parameter space explored is summarised in table 3.5. The time dependent values of N_{Lyc} and L_{mech} were derived from simulations using the code Starburst 99¹ (Leitherer et al. 1999). This simulation was carried out for solar metallicity and a Salpeter initial mass function with an upper mass cut-off of $100 M_{\odot}$. These values were obtained both for a continuous and an instantaneous star formation history for a particular value of star formation rate (SFR) and subsequently scaled linearly for other values of SFR. For a given combination of input parameters, the radius and velocity of the shock front (almost the same as that of the ionized gas), mass of ionized gas, ionization rate and the gas density were computed. These calculations were carried out using the expressions in Shull (1980) for the appropriate phase of the nebula. At the beginning of the expansion, as long as the thermal energy is larger than the mechanical energy in the stellar wind, the dynamics is assumed to be determined only by the thermal pressure of the ionized gas inside the Strömgren sphere. Since the ionizing photon rate N_{Lyc} is a function of time, Spitzer's expression for the shock radius is modified to

$$\frac{4}{7} R_s(t)^{7/4} = c_i \left(\frac{3}{4\pi\beta_2 n_0^2} \right)^{1/8} \int_0^t (N_{\text{Lyc}})^{1/4} dt + \frac{4}{7} R_{is}^{7/4} \quad (3.1)$$

where R_{is} is the initial Stromgren sphere, which is calculated for the ionization rate at the first timestep. For the energy conserving portion of the snowplow phase, the radius and velocity of

¹URL: <http://www.stsci.edu/science/starburst99/>

the shock front are given by

$$R_s(t) = 6.57 \times 10^4 \left(\int_0^t L_{36}(t) dt \right)^{1/5} \left(\frac{n_o}{10^5 \text{ cm}^{-3}} \right)^{-1/5} \left(\frac{t}{\text{yr}} \right)^{2/5} \text{ pc} \quad (3.2)$$

$$V_s(t) = 128.12 \left(\frac{n_o}{10^5 \text{ cm}^{-3}} \right)^{-1/5} \left[2 \left(\frac{t}{\text{yr}} \right)^{-3/5} \left(\int_0^t L_{36}(t) dt \right)^{1/5} + L_{36}(t) \left(\frac{t}{\text{yr}} \right)^{2/5} \left(\int_0^t L_{36}(t) dt \right)^{-4/5} \right] \text{ km s}^{-1} \quad (3.3)$$

and for the momentum conserving phase, by

$$R_s(t) = R_s^c \left[1 + \frac{12}{5} \left(\frac{t}{t_c} - 1 \right) + c_1 \left(\frac{t}{t_c} - 1 \right)^2 \right]^{1/4} \quad (3.4)$$

$$V_s(t) = \frac{R_s^{c4}}{4R_s^3} \left[\frac{12}{5t_c} + \frac{2c_1}{t_c} \left(\frac{t}{t_c} - 1 \right) \right] \quad (3.5)$$

where the expressions for c_1 , t_c and R_s^c are obtained from Shull (1980). t_c defines the time when the bubble transits from the energy conserving phase to the momentum conserving phase and R_s^c is the shock radius at time t_c . In the energy conserving phase, the total mechanical energy imparted to the shell by the stellar wind starting from $t=0$ up to time t determines the dynamics of the system. The mechanical luminosity is also a function of time. Hence, the radius and velocity of the shock front at time t will depend on $\int_0^t L_{36}(t) dt$. This modifies the familiar dynamical equations to those in eqn. 3.2 and eqn. 3.3. The derived values of the dynamical quantities, the ionization and the density and mass of the ionized gas as a function of time were compared with the values derived from the RRL modelling, listed in table 3.5. Acceptable solutions were identified which were consistent with the imposed constraints. Table 3.5 summarises the allowed values of the input parameters. The following assumptions have been made in the above analysis, namely, (1) constant ambient density, (2) the total L_{mech} of the cluster is the sum of the mechanical wind luminosities of the individual stars and hence wind-collisions are neglected, (3) the mass loss rate and asymptotic wind velocity are calculated from the total L_{mech} and the total momentum flux (4) the gas adjusts to the changing N_{Lyc} and L_{mech} faster than the time step in the computation, (5) when the wind-driven ionized gas shell is formed, it traps all the ionizing photons, (6) the transition between various regimes is abrupt, and (7) the star formation history is assumed to be either continuous or instantaneous.

With the above assumptions, gas dynamics narrowly constrains the properties of the supernebula. The derived solutions correspond to wind-driven shells in the energy-conserving phase only. The allowed age of the nebula (and hence the cluster) is $\sim 2.5 \times 10^4$ years, corresponding to a diameter of 7–8 pc; no solutions for smaller sizes were found. These values are a strong constraint on the hypothesized SSC. The time dependence of the radius and velocity of the shock front for a typical model solution is shown in figure 3.11. As expected, the age of the nebula derived from this detailed computation is very close to the dynamical age calculated as $\sim \text{radius/velocity}$. However, the reliability of these values depends on the accuracy of the Starburst 99 code for young clusters, as discussed below.

Table 3.5: Dynamical modelling details for an expanding stellar wind-driven nebula

Parameter	Explored Range	Solutions obtained
<i>Parameter space for the inputs to the model</i>		
Ambient density (n_0 , cm^{-3})	10^{-3} – 10^6	200–400
Age of cluster (yrs)	10^4 – 10^8	$(2\text{--}3.5)\times 10^4$
SFR ($M_\odot/\text{yr}$)	0.1–100.0	2.5–6
<i>Parameter space for observational constraints</i>		
Radius of shell (R_s , pc)	0.2–4.0	3.5–4.0
Velocity of shell (V_s , km s^{-1})	80–120	85–115
Mass of ionized gas ($M_\odot$)	1250–5000	1250–2400
N_{Lyc} (photons s^{-1})	$6\text{--}24\times 10^{51}$	$6\text{--}10\times 10^{51}$
Density of ionized gas (n_e , cm^{-3})	$(4\text{--}25)\times 10^3$	$(18\text{--}25)\times 10^3$

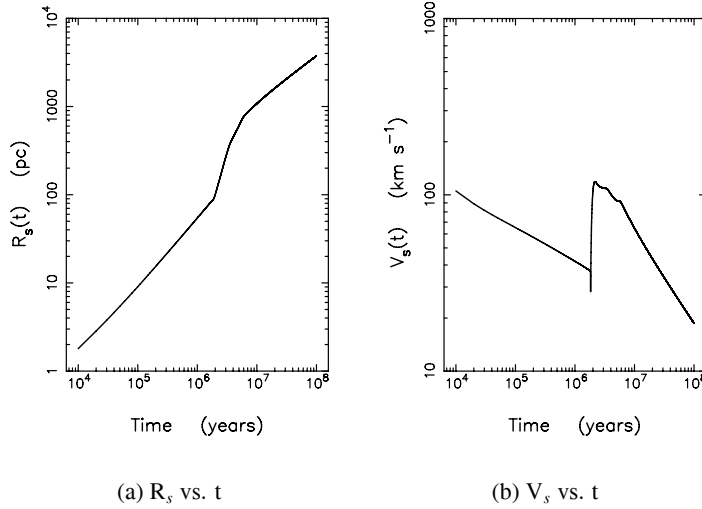


Figure 3.11: Radius and velocity of the shock front for a solution consistent with the imposed constraints. The age of the nebula is 25000 years. The abrupt change in the shock velocity near $t=2\times 10^6$ years occurs since we model the transition between the various phases of expansion as an instantaneous process. However, this abrupt transition does not significantly affect the results; see fig 6 of Strickland & Stevens (1999).

Given the uncertainty of stellar tracks for very young star, the values of N_{Lyc} and L_{mech} predicted by the Starburst 99 code are not accurate to more than a factor of a few for $t < 5\times 10^5$ years (Leitherer, private communication). The radius of the shock front is $R_s \sim (\int L_{\text{mech}} dt)^{1/5}$ in the energy-conserving phase. Since L_{mech} is a monotonically increasing function of time (up to 5×10^6 years for a continuous SFR), the dynamics of the nebula at $t > 5\times 10^5$ years is insensitive to the uncertainties in the Starburst 99 model at earlier times. Hence, since we do not obtain any solution for a time greater than 5×10^6 years, we can conclude that a nebula older than this age will not be able to explain the observations, even after taking into account the inaccuracies in the code for shorter times. The only consistent nebular age estimate derived is $\sim 2.5\times 10^4$ years. The inputs from the Starburst 99 code are not accurate for such short timescales. Nevertheless it can

be shown that since the ratio between L_{mech} and N_{Lyc} is constant with time in the Starburst 99 model, if just the functional dependence of L_{mech} with time for $t < 5 \times 10^5$ years, as opposed to the absolute values themselves, is reliable, then the model results are relatively independent of the uncertainties in the Starburst 99 codes. However, given the short ages derived, it can be expected that the star formation at this timescale, and hence the value of L_{mech} and N_{Lyc} , is stochastic. In such a case, the model described here is not applicable. Even for a stochastic star formation process, the short dynamical timescale of 10^4 years still needs to be explained. The dynamical model implicitly assumes that the star cluster is spatially within the wind-blown structure, which need not be true if the gas is within a region of size ≤ 4 pc. The model also assumes that the stellar winds of the individual stars add coherently to produce a net ‘cluster-wind’. This assumption will be violated for a young cluster due to stellar-wind collisions and YSO outflows. These factors may help confine the gas for a time much longer than the dynamical age. They also provide a natural way of increasing the line width by stirring up the intra-cluster medium. Hence if a star cluster is invoked as an ionizing source, it must be fairly young, though the properties of such a young cluster cannot be easily predicted. A HII region exhibiting wide lines has been discovered surrounding a star cluster in the dwarf starburst galaxy NGC 5253 and the issues related to the detection of a nebula with a very short dynamical age is discussed further in chapter 4.

In this section, the ionizing source for the line emitting gas is assumed to be a star cluster and the thermal gas is assumed to be in the form of a stellar-wind blown bubble. The dynamics of this nebula have been modelled and the results compared with the observational constraints. Consistent solutions are obtained only for a nebular age of ~ 25000 years. We consider as improbable the existence of a star cluster with almost 500 O stars which is as young as the value derived here. Though the model used in this calculation is simple and the inclusion of additional features like mass loading might well increase the age of the cluster, such a case is ill-constrained.

3.3.2.3 A weak AGN as an ionizing source

Turner & Ho (1985) discovered that the nucleus is unresolved in the radio continuum, and has a high brightness temperature and hence suggested a possible AGN at the nucleus. Ulvestad & Antonucci (1997) also arrived at the same conclusion based on their higher-resolution images (size $< 0.05''$ and $T_B > 22000$ K). If the nucleus does contain an AGN, then its UV continuum can be invoked to ionize the RRL emitting gas. The expected UV luminosity can be estimated using the observed radio continuum and X-ray luminosities. Assuming a central AGN, the velocity dispersion ($\sigma_v = 85 \text{ km s}^{-1}$ corresponding to the FWHM of 200 km s^{-1}) of the RRLs, along with the maximum possible size of the ionized gas (radius of 2 pc), can be used to constrain the maximum mass of the central object. This central mass ($\sigma^2 r / G$, with a numerical coefficient depending on the assumed line profile, taken to be unity) is derived to be less than $3 \times 10^6 M_\odot$.

Powerful AGNs are powered by a geometrically thin optically thick standard accretion disk whose blackbody emission peaks in the UV, called the Big Blue Bump, or BBB (Koratkar and Blaes 1999). If the AGN at the nucleus of NGC 253 also has a standard accretion disk, with a BBB, the latter can be invoked as the ionizing source. Falcke et al. (1995) showed that this BBB luminosity from the disk is correlated with the core radio emission (νL_ν at 2 cm) for a sample

of quasars. This correlation was explained in terms of a jet-disk symbiosis model. The value of (νL_ν) at 2 cm for the nucleus of NGC 253 is about a hundred times less than the faintest quasar in their sample. If the relation they observe is assumed to hold even for such faint luminosities, then we can estimate the UV disk luminosity to be about 10^{42} ergs s^{-1} by extrapolating the correlation for the radio-weak quasars. If photons with energies between 13.6 eV and ~ 30 eV are assumed to contribute to the ionization of hydrogen, then the ionizing photon flux is given by

$$N_{\text{Lyc}} = L_{\text{uv}} \left(\int_{13.6}^{30} \frac{\nu^n}{h\nu} d\nu \right) / \left(\int_{13.6}^{30} \nu^n d\nu \right) \quad (3.6)$$

where n is the spectral index of the UV continuum. For a range of spectral indices, the estimated disk luminosity of 10^{42} ergs s^{-1} implies an ionizing photon flux of $\sim 2 \times 10^{52}$ s^{-1} . This value is consistent with what is needed to explain the observed RRLs. Based on the derived UV luminosity, the value of L_{2-10} can be computed in the standard accretion disk model (Frank, King and Raine 1985). The UV (13.6–30 eV) and X-ray (2–10 keV) fluxes and hence their ratio is calculated using

$$F_\nu \propto \nu^{1/3} \int_{x_1}^{x_2} \frac{x^{5/3}}{e^x - 1} dx, \quad \text{where} \quad x_1 = \frac{h\nu}{kT_*}; \quad x_2 = \frac{h\nu}{kT_{\text{out}}} \quad \text{and} \quad (3.7)$$

$$T_* = \left(\frac{3GM\dot{M}}{8\pi R_*^3 \sigma} \right)^{1/4} \quad \text{and} \quad T_{\text{out}} = T_* \left(\frac{R_{\text{out}}}{R_*} \right)^{-3/4}$$

The accretion rate $\dot{M}$ and the inner radius R_* are taken as free parameters. It was found that the thin disk model under-predicts L_{2-10} for most values of $\dot{M}$ and R_* , and is consistent with observations only for super-eddington accretion rates. Hence a standard optically thick disk cannot produce both the observed X-ray flux and the derived UV flux.

However, given the low radiative efficiency of the nucleus (the accretion rate is estimated to be about a thousandth of the eddington rate, based on the upper limit to the central mass and the UV luminosity estimated from the ionization rate), the AGN could be powered by an ADAF disk (Narayan, Mahadevan and Quataert 1998). ADAF models predict the absence of a BBB since most of the emission is from much hotter plasma and hence peaks in the X-ray wavelengths. The 2 cm radio luminosity of the nucleus of NGC 253 implies that the AGN is of low luminosity (LLAGN; Nagar et al. 2000) and these LLAGNs have been shown not to exhibit a BBB in their UV emission (Ho 1999). Hence, in the ADAF model, we shall attempt to explain the ionization from the X-ray luminosity instead. In this scenario, we assume that the emission from the UV up to X-rays arises from a single power law and that the UV portion of this emission is responsible for all of the ionization rate derived from the RRL models. Pietsch et al. (2001) showed (using *XMM-Newton*) that the X-ray source at the centre of the galaxy is unresolved at energies higher than 2 keV and is coincident with the radio nucleus. At lower energies, the peak of the X-ray emission shifts southwards and the size of the source increases. This was explained by invoking a high obscuration in the soft X-ray band. They modeled the emission from the nuclear X-ray source as bremsstrahlung radiation from a three-temperature plasma. For simplicity, we shall assume that the UV up to X-ray emission is bremsstrahlung radiation from plasma at a single temperature, T_x . The UV portion of the emission is constrained to produce an ionizing photon flux greater than that needed to explain the RRLs and the 2–10 keV portion is normalized to the observed value. A fraction f of the ionizing photons produced is assumed to be incident on the

thermal plasma which subsequently produces the observed RRLs. The temperature T_x , f , and the size of the plasma R are free parameters in the calculation. The number of ionizing photons incident on the line emitting gas is computed by integrating the spectrum from 13.6 eV up to an energy where the photo-ionization optical depth $\tau_\nu = n_{H_o} a_\nu R = n_e a_\nu R$ becomes unity and hence the ratio is given by

$$\frac{L_{2-10}}{N_{\text{Lyc}}} = \frac{1}{f} \left(\int_{2\text{keV}}^{10\text{keV}} e^{-\frac{h\nu}{kT_x}} d\nu \right) / \left(\int_{13.6\text{eV}}^{\nu_{\tau_\nu=1}} \frac{1}{h\nu} e^{-\frac{h\nu}{kT_x}} d\nu \right) \quad (3.8)$$

where f and R are free parameters in this computation, with the condition that $R < 2.5$ pc. The required ionization is found to be consistent with the observed X-ray flux only for $T_x < 0.2$ keV for any value of f and R considered. Therefore the 2–10 keV emission would arise in the exponentially decaying tail of the free-free emission of this plasma. Since this is unlikely, especially because Pietsch et al. (2001) have detected significant emission up to 10 keV, we interpret our result to imply that the X-ray emission is too weak to explain the required ionization.

We have shown that if the accretion disk emission is assumed to exhibit a Big Blue Bump, then the required ionization can be readily explained. The extinction towards the nucleus would be consistent with the non-detection of this excess UV continuum emission. However, its X-ray emission falls short of the observed value. On the other hand, the nucleus of NGC 253 possibly contains a low luminosity AGN which, if powered by an ADAF, will not exhibit a BBB in its spectrum. Without this excess BBB emission though, the observed X-ray luminosity is inadequate to explain the needed ionization. This problem is reminiscent of LINER 2s, a population whose ionization and energy source is not yet understood (Terashima, Ho and Ptak 2000) and one of the additional sources of ionization considered for these LINER 2 sources is a star cluster. ADAF models also predict the X-ray emission for a given radio flux and mass of the black hole (Yi and Boughn 1998)

$$L_{\text{radio}}(\nu L_\nu) = 7 \times 10^{35} \left(\frac{\nu}{15 \text{ GHz}} \right)^{7/5} \left(\frac{M}{10^7 M_\odot} \right) \left(\frac{L_{2-10}^X}{10^{40} \text{ erg s}^{-1}} \right)^{1/10} \text{ erg s}^{-1} \quad (3.9)$$

where M is the mass of the accreting black hole. Using the calculated upper limit to the black hole mass of $3 \times 10^6 M_\odot$, the expected 2–10 keV X-ray luminosity can be calculated for this model. This X-ray luminosity is a hundred times less than that observed (and is ten times less than the ratio observed in other LLAGNs; Ulvestad & Ho 2001). The deficit by a factor of 10 for the sample of five LLAGNs was explained by Ulvestad & Ho (2001) as an excess of radio emission due to possible pc-sized unresolved jets. A further factor of ten in the case of NGC 253 is troublesome.

An alternate way of explaining the radio, UV and X-ray data is that of Quataert et al. (1999) who model the spectrum of two LLAGNs which have an X-ray to UV ratio which is too large for a thin disk and too small for an ADAF disk. Following their work, which tries to explain the SEDs of these two LINERS, we hypothesize that in the AGN which is presumed to exist at the nucleus of NGC 253, the accretion disk is an ADAF in the inner part and beyond a certain radius, becomes the standard thin disk. In this scenario, most of the X-ray emission in the 2–10 keV band will arise in the ADAF part of the disk and the radio and the corresponding BBB will arise in the outer thin disk. One would indeed expect an inner ADAF disk to give way to a standard thin disk beyond a certain radius.

3.3.3 Summary and Discussion

RRLs have been detected from the radio nucleus with a FWHM of 200 km s^{-1} within a region of size 4 pc. The radio nucleus is an unresolved source with high continuum brightness temperature, and is hence believed to host an AGN. We have investigated various possible ionizing sources for the line emitting thermal gas in an attempt to deduce the nature of the radio nucleus. The first model considered is that of a compact supernova remnant expanding in a dense medium. It is shown that all of the observed parameters cannot be explained in this model and hence an SNR is ruled out. Next we consider a star cluster situated internal to the line emitting gas, and this gas is assumed to be in the form of a stellar wind-blown bubble. Modelling the dynamics of this bubble shows that the age of such a nebula is 25000 years. It is improbable that a star cluster this dynamically young, has produced enough OB stars to generate an ionization of $>6 \times 10^{51} \text{ s}^{-1}$. However, within this model of a wind-driven bubble, it is not possible for the nebula to have a substantially longer age. Hence the only way the ionizing source can be a star cluster is by invoking a scenario wherein the line width is as broad as 200 km s^{-1} but the bulk motion of the gas is much less than this. Such a scenario is difficult to construct. Lastly we consider an AGN model and show that the required UV luminosity can be explained by extrapolating the properties of bright QSOs. However, in order to explain the radio, UV and the X-ray luminosities, a simple accretion disk model is insufficient and a hybrid disk model is hypothesized. Based on these arguments, we favour an AGN as the possible ionizing source. Recently, Weaver et al. (2002) observed NGC 253 with the *Chandra* Observatory and detected a heavily absorbed ionizing source in hard X-rays seen through a dusty torus with a column density $N_{\text{H}} \sim 2 \times 10^{23} \text{ cm}^{-2}$. They suggest that the ionizing source is either an intermediate-mass black hole or a low luminosity black hole. They also suggest that the large column density of absorbing material can explain the large value of the ratio between the UV luminosity and the X-ray luminosity derived by us in the ADAF model. This observation supports our conclusion that the ionizing source responsible for the recombination line emission is a low luminosity AGN. In any case, the presence of an AGN within the radio nucleus is now confirmed. However, yet another scenario can also explain the observed RRLs. There could well exist a star cluster along with the AGN inside the 4 pc region (the central 2 pc region of our Galaxy hosts both a massive low luminosity black hole of mass few times $10^6 M_{\odot}$ as well as a number of hot stars). In such a case, the ionization of the line emitting gas could be due to the star cluster and the line width could arise due to the bulk motion of the gas in the gravitational potential of the AGN. We discuss such a possibility in greater detail in section 3.4.4. However, we do not attempt to model such a configuration since there exists too many unconstrained free parameters in such a model.

3.4 Extended RRL emission

In this section, the extended line emission at 1.4 GHz, 8.3 GHz and 15 GHz are studied in detail. The 1.4 GHz continuum image is first discussed in the next subsection, following which the RRL emission is dealt with.

3.4.1 The continuum images

The 1.4 GHz continuum emission from NGC 253 and its surroundings, imaged over a region of size 1° (two primary beams) using the C configuration data, is shown in the figure 3.12a. A number of sources can be identified outside the main disk of emission. Of these, we associate nine sources, which are situated within a region of size $20'$ centred on the galaxy, with the galaxy itself, based on the spatial extent of the 330 MHz continuum emission (Carilli et al., 1992). We have named these sources in increasing order of R.A. as S1 to S9 and have marked them in figure 3.12b. Of these nine sources, the three inner most sources, S3, S4 and S6, were detected by Anantharamaiah & Goss (1990) and by Ulvestad (2000). Since the images presented in Ulvestad (2000) were constructed from data obtained with a large bandwidth, sources far away from the phase centre suffer from bandwidth smearing. Hence they did not present their images for these three sources. All the nine sources identified can be seen in the 330 MHz images of Carilli et al. (1992) and Carilli (1996). We have also identified these sources in our BnA configuration continuum image. The positions and the flux densities of the sources were measured from three images: the C configuration ‘natural weighted’ image, the BnA configuration ‘natural weighted’ image and a higher resolution BnA configuration image produced by providing less weightage to the data at smaller uv distances (robustness parameter, as defined by Briggs 1999, of 0). The synthesized beams for these images are $34.7'' \times 17.0''$, $5.1'' \times 3.8''$ and $3.8'' \times 2.6''$ respectively and the rms noise in the images are 0.2, 0.14 and 0.1 mJy/beam respectively. The image parameters, measured by fitting a two-dimensional gaussian using the AIPS task JMFIT, are listed in table 3.6. The C and BnA configuration images will hereafter be referred to as the C and B images respectively. For sources unresolved even in the B image, we quote the flux density and position in the B image. If the source is resolved in the B image, then we measure the total flux density from the C image and the position from the B image.

Table 3.6: Continuum sources in the 1.4 GHz image

Source name	Position (B1950.0)		S _{1.4 GHz} (mJy)	Source size	Comments
	α (00 ^h)	δ (−25°)			
S1	44 ^m 32 ^s .65	40'11''.2	3.4	U ^a	B1; resolved in B image (R=0) B2; resolved into 3 point sources real feature ?; not seen in B image B3; resolved in B image possibly resolved Not seen in B image
S2	44 ^m 35 ^s .95	26'52''.6	10.8	4.0''×1.6''	
S3 ^b	44 ^m 44 ^s .57	34'06''.0	19.0	0.5''×0.4''	
S4 ^b	45 ^m 17 ^s .56	30'00''.0	25.4		
S5 ^b	45 ^m 27 ^s .50	28'53''.0	1.8	U	
S6	45 ^m 31 ^s .57	34'53''.7	56	2.4''×0.5''	
S7	45 ^m 34 ^s .03	43'59''.7	7.2	3''×1''?	
S8	45 ^m 33 ^s .79	32'49''.1	1.6	U	
S9	45 ^m 37 ^s .70	27'34''.9	2.8	U	
15 ^c	45 ^m 06 ^s .12	31'55''.3	2.0	2''×2''	possibly resolved; U00=2.4 mJy
19 ^c	45 ^m 12 ^s .07	32'55''.7	1.2	4.5''×2.1''	U00=2.4 mJy
20 ^c	45 ^m 13 ^s .13	33'01''.1	3.5	4.1''×3.4''	U00=6.1 mJy
22 ^c	45 ^m 15 ^s .75	32'01''.2	1.5	8.6''×5.6''	within weak diffuse em. U00=1.2 mJy
23 ^d	45 ^m 12 ^s .91	31'23''.9	0.6	—	too weak to resolve
24 ^d	45 ^m 15 ^s .69	31'51''.2	0.9	—	too weak to resolve
25 ^d	45 ^m 16 ^s .80	32'13''.9	0.7	—	too weak to resolve

^aU - unresolved, even in the B configuration images.

^bThese are within 2-3 synthesized beams of –ve extended emission in the C configuration image.

^cSources in U00 (Ulvestad 2000) with inaccurate flux densities, positions.

^dSources seen in B image but not in Ulvestad (2000).

S5 and S8 are seen only in the C image and are probably sufficiently resolved out in the

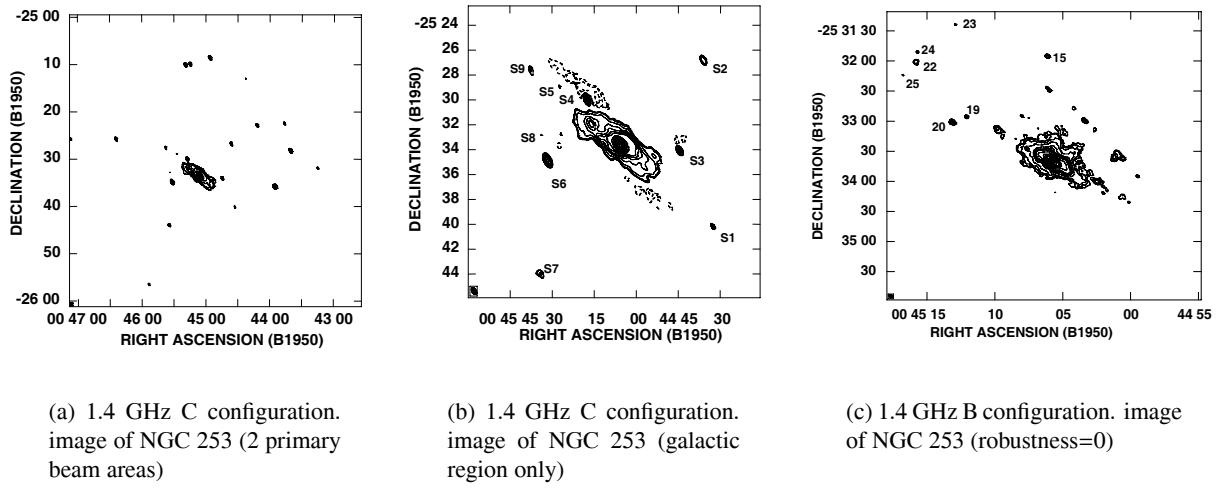


Figure 3.12: 1.4 GHz continuum emission from NGC 253. **(a)** ‘Natural weighted’ image of the $1'$ area (2 primary beams) around NGC 253, without applying primary beam correction. The synthesized beam is $34.7'' \times 17.0''$ at a P.A. of 26° and the rms of the image is 0.2 mJy/beam. The contour levels are in steps of (7, 20, 40, 80, 160, 320, 640, 1280, 2560, 5120) times the rms. **(b)** A close-up of the same image, showing only those sources identified with the galaxy, based on the 330 MHz extended emission. The contour levels are in steps of (-20, -10, -7, 7, 10, 20, 40, 60, 80, 100, 200, 400, 600, 800, 1000, 2000, 4000, 6000, 8000) times the rms. **(c)** B configuration. image with robustness parameter of zero (higher resolution than the natural weighted image). The area shows the sources detected by Ulvestad (2000). The synthesized beam is $3.8'' \times 2.6''$ at a P.A. of 61° . The rms of the image is 0.1 mJy/beam and the contour levels are in steps of (5, 7, 10, 20, 40, 60, 80, 100, 200, 400, 600, 800, 1000, 2000, 3000, 4000) times the rms. Negative contours are below -5σ .

B image so that the surface brightness is below the sensitivity limit. The flux densities of S3, S4 and S5 are uncertain since they are within 2-3 synthesized beams from extended negative emission in the C image caused by missing short spacings. Hence only the B image is used in determining the parameters of S3 and S4. Given the low flux density, proximity to negative emission in the C image and the non-detection in the B image, the reality of S5 is doubtful and needs to be confirmed. Apart from the three sources B1 (our S3), B2 (our S4) and B3 (our S6), Ulvestad (2000) also identified 22 circumnuclear sources within the inner $3'$ (<2 kpc) of the galactic centre. These sources can be seen in the B configuration image shown in figure 3.12c. Out of the twenty two sources listed in their paper, four, numbered as 15, 19, 20, and 22, have uncertain flux densities and positions due to significant primary beam corrections and bandwidth smearing. Since these effects are minimal in our B image, we derive the positions and flux densities of these sources, which are also included in table 3.6. Additionally, we also detect three new sources in the B image, numbered 23, 24, 25 which are listed in the table and also marked in figure 3.12c. We quote only the peak fluxes of these sources since the signal to noise ratio is not high enough to attempt a spatial deconvolution in order to determine the sizes.

Two spurs of emission extending NW from the disk can be seen in the B image, roughly at R.A. $00^h 45^m 4^s.5$ and $00^h 45^m 5^s.5$. Since the signal to noise ratio of these two features is quite high, it is improbable that these are image processing artifacts but, instead, are possibly the small scale (~ 100 pc) features associated with the kpc-scale outflows from the centre of the galaxy. However, there are no corresponding features in the C configuration, which is surprising. The

peak flux densities of the continuum emission measured in the C and B images are 2.0 Jy/beam and 67.5 mJy/beam respectively. When the B image is convolved to the resolution of the C configuration image, the peak continuum flux density in the convolved image was found to be 2.0 Jy/beam as well. Therefore, we conclude that in the inner $\sim 35''$ region, the B image contains all of the flux as in the C image. This is presumably because much of the the inner uv portion of the C data was flagged before imaging.

3.4.2 The H92 α line images

In this section, the morphology of the extended H92 α line emission is studied. The line parameters of the four compact line sources west of the nuclear region as well as that of the line emission from the central 15 pc region are derived.

As mentioned above, the H92 α line emission at 8.3 GHz is detected from a prominent 15 pc sized extended region as well as from four other distinct sources in the disk. The results of gaussian fits to the spectra towards the peak of the line emission in the four compact sources are listed in table 3.7, along with those for the entire ‘15 pc region’ as well as for the ‘25 pc region’ (which includes the ‘15 pc region’, 5.72–40.1 and 5.75–39.9). Since the signal-to-noise of the extended emission is not very large, the total integrated line flux depends on the exact boundary within which the line emission is summed. The line emission in the extended 15 pc and 25 pc sized regions was summed over all pixels whose emission is greater than 2σ in the channel images. The total H92 α recombination line flux thus computed is $25.5 \times 10^{-23} \text{ W m}^{-2}$. Anantharamaiah & Goss (1990) imaged the H92 α emission from NGC 253 using the VLA in the C and D configurations at a much lower resolution of $7.4'' \times 5.2''$, which covers all of the line emitting regions identified in this work. They derive a total integrated line flux of $44 \times 10^{-23} \text{ W m}^{-2}$. The remaining line emission of $\sim 18 \times 10^{-23} \text{ W m}^{-2}$, not detected by our high resolution observations, must be spread over a much larger region. In such a case, we would not be able to detect this large scale H92 α emission because (1) the line flux within a synthesized beam in the A configuration would not be significantly higher than the rms of 0.12 mJy/beam or (2) this emission is resolved out due to missing short spacings in the interferometric observations, or a mixture of both.

As discussed in section 3.2.2, the association of the four compact line emitting objects with compact continuum sources is not exact. The observed correspondence, however, is close enough for three of the sources that we can confidently claim a true association. In the case of the fourth line emitting object near the continuum source 5.75–39.9, a true continuum counterpart probably does not exist. However, we shall identify this line emitting object with this continuum object for ease of nomenclature. The observed positional offsets for the other three sources, though small, could either be real, or could be due to the low signal to noise ratio of the line features. Since the continuum emission is dominated by non-thermal radiation and RRLs arise in thermal gas, a genuine spatial offset between the two emissions could well exist, as in the case of NGC 1808 at high resolution (Kotilainen et al., 1996).

Table 3.7: H168 α , H92 α and H75 α line parameters for NGC 253

Source	Peak flux density (mJy/beam)	Central velocity ^a (km s ⁻¹)	FWHM ^b (km s ⁻¹)	Integrated flux ($\times 10^{-23}$ W m ⁻²)
<i>1.4 GHz H92α line emission</i>				
7.4'' $\times$ 5.2'' area	1.8 $\pm$ 0.1	200 $\pm$ 20	160 $\pm$ 14	1.6 $\pm$ 0.25
<i>8.3 GHz H92α line emission</i>				
5.49–42.3	0.5 $\pm$ 0.1	201 $\pm$ 7	73 $\pm$ 17	1.2 $\pm$ 0.3
5.59–41.6	0.5 $\pm$ 0.1	172 $\pm$ 7	65 $\pm$ 16	1.0 $\pm$ 0.3
‘25 pc region’ ^{c,d}	4.2 $\pm$ 0.2	195 $\pm$ 4	186 $\pm$ 9	23 $\pm$ 2
5.72–40.1	0.46 $\pm$ 0.09	170 $\pm$ 15	101 $\pm$ 23	1.4 $\pm$ 0.3
5.75–39.9	0.54 $\pm$ 0.09	175 $\pm$ 10	112 $\pm$ 20	1.8 $\pm$ 0.3
‘15 pc region’ ^{d,e}	3.2 $\pm$ 0.15	194 $\pm$ 5	211 $\pm$ 12	20 $\pm$ 2
<i>15 GHz H75α line emission</i>				
Nucleus	1.8 $\pm$ 0.3	224 $\pm$ 17	230 $\pm$ 40	23 $\pm$ 3
5.76–39.9	1.6 $\pm$ 0.3	205 $\pm$ 18	230 $\pm$ 43	20 $\pm$ 3

^aHeliocentric velocity, optical definition.

^bNo corrections for hanning smoothing or finite resolution have been made.

^cIncludes the ‘15 pc region’ and the sources 5.72–40.1 and 5.75–39.9, summed over pixels $> 2\sigma$.

^dThe rms noise in the spectrum was calculated by computing the rms for an ensemble of spectra for areas of identical size in the line cube.

^eThe central region shown in figure 3.5b, summed over pixels with intensity $> 2\sigma$.

The line emission in the ‘15 pc region’ has a complex morphology. Four apparently distinct sources can be identified by visually inspecting the channel maps made with various resolutions. The existence of more than four sources contributing to the observed emission cannot be, a priori, ruled out. Indeed, diffuse emission at the low signal-to-noise of our data could well masquerade as a possible compact source. These four sources cannot be resolved from the each other in the naturally weighted image, except in selected channels. However, higher resolution channel images constructed by downweighting the short spacings clearly delineate the different sources, as can be seen in figures 3.6b. The spectra of each of the four sources do not have identical line profiles, which would explain why each of these sources can be resolved from the emission of the others in different channels. For example, in figure 3.6, the southern source is most clearly visible at velocities 119.0 and 90.8 km s⁻¹ whereas the westernmost source is seen best at a velocity of 203.6 km s⁻¹. The two remaining northern sources are well resolved at velocities of 231.9 and 260.1 km s⁻¹. Though the westernmost source in the 15 pc region is well identified in the various channel images and the parameters of the line towards the peak of the line emission are similar to those of the other three sources, a spurious feature is also seen in the spectrum towards the low velocity end.

We attempt to deconvolve the four sources in the channel images using the AIPS task JMFIT, in order to derive the spatial positions and line parameters for the four sources in the 15 pc region. Each of these sources are assumed to be unresolved and hence their spatial profiles are assumed to be that of the CLEAN beam. The true positions of the four sources are expected to be the same in all channels. Hence, simultaneous deconvolution of all four sources was attempted in each channel, using line cubes constructed at different spatial resolutions. However, due to the low signal to noise ratio of the four sources, we did not obtain consistent results. Hence, an alternate method was used in order to derive the positions of the sources.

Table 3.8: Positions of the H92 α and H75 α line emitting sources in the ‘15 pc region’

Source	RA (B1950.0)	Dec (B1950.0)
<i>The four H92α sources</i>		
1	00 ^h 45 ^m 05 ^s .753 (2)	−25° 33′ 38″.95 (5)
2	00 ^h 45 ^m 05 ^s .773 (2)	−25° 33′ 39″.54 (5)
3	00 ^h 45 ^m 05 ^s .777 (1)	−25° 33′ 38″.98 (2)
4	00 ^h 45 ^m 05 ^s .795 (1)	−25° 33′ 39″.05 (2)
<i>The second H75α source</i>		
source 2 ^a	00 ^h 45 ^m 05 ^s .770 (2)	−25° 33′ 38″.91 (5)

^aThe position of the second source to the west of the nuclear line emission is determined after aligning the position of the H75 α line emission from the nucleus with that of the H92 α line emission.

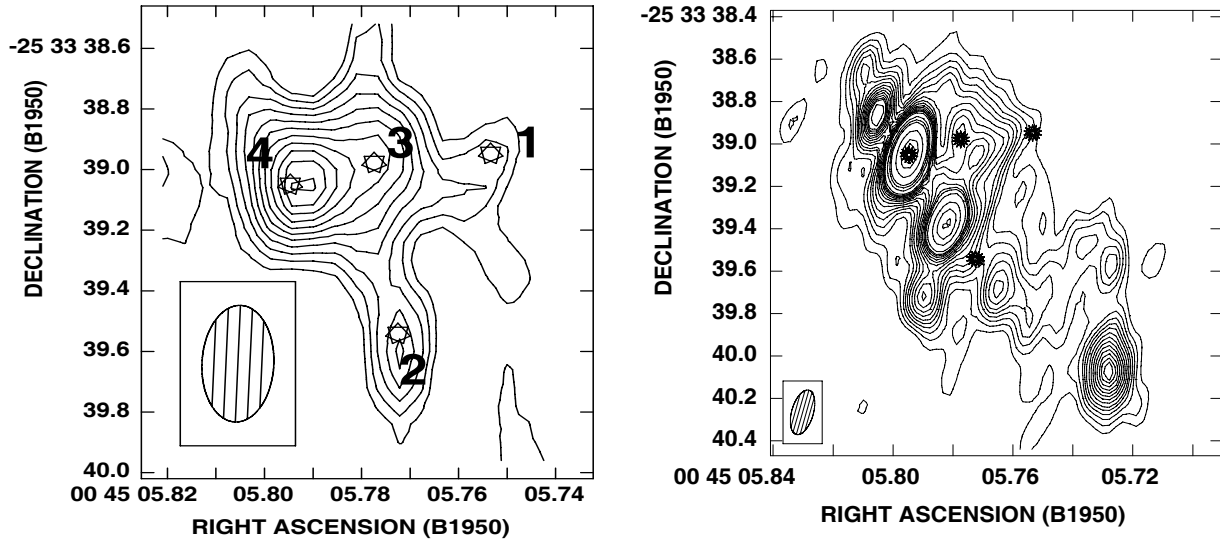
NOTE: The numbers within parenthesis are the gaussian fitting errors in the last decimal of the listed values, as quoted by the AIPS fitting routine JMFIT. These positions are not absolute positions, i.e., the errors are not absolute positions uncertainties. Instead, these are relative position, and the coordinates of source 4, the radio nucleus, can be taken to be assumed.

For each of the four sources, one or more channels were identified in one or more line cubes (of different resolution) where the source was seen to be most clearly resolved from the surrounding emission and the peak positions derived from such channels were taken as the actual positions of the sources. The values of the positions derived in such a manner are, to an extent, subjective and prone to systematic error. However, the line emission is not significantly strong; the peak intensities of two of the sources are $\sim 8\text{--}9\sigma$ and of the remaining two are $\sim 5\text{--}6\sigma$. Hence, given the low signal-to-noise and the resolution, which is about a factor of two worse than what is required to resolve the various sources, the method adopted is adequate and also sufficient to yield numbers consistent with the noise level. The derived positions of the four sources are listed in table 3.8. Note that these positions are not absolute positions. The continuum and line data have been shifted in order to align the field sources with the image of UA97 (see section 3.2.2). Hence, the source positions listed in the table are intended to be relative to that of the radio nucleus (source 4), whose coordinates can be taken to be assumed. The errors in the positions quoted in the table are estimated from the gaussian fitting procedure and are consistent with the expected values computed using the expressions in Rieu (1969). The exercise described above was used only to derive the spatial positions of the four sources and not their individual spectral properties. Following this, the individual channel data of the naturally weighted images (of maximum sensitivity and largest synthesized beam size) were deconvolved, holding the positions of the four sources fixed at the values derived using the higher resolution images. This procedure was expected to yield reliable spectra of each source. However, for channels which were outside the FWHM of the lines, the deconvolution procedure was not successful due to the decreased signal to noise ratio. Hence individual deconvolved spectra were not obtained.

Figure 3.13a shows the integrated H92 α emission at a resolution of $0.38'' \times 0.20''$ imaged by summing over pixels whose intensities are greater than 1σ . The positions of the four sources, which are listed in table 3.8, are marked in the figure using ‘star’ symbols. The peaks of emission do not coincide with the positions of these symbols; however, these ‘star’ symbols represent the positions of the peak of the line emission in those channels where a given source is spatially

well resolved and hence the observed offsets in the figure are probably due to blending on line emission from the four sources due to inadequate spatial resolution.

We compare the integrated line emission with high resolution continuum images in order to identify possible continuum counterparts to the four H92 α line emitting sources. Shown in figure 3.13b is the 15 GHz continuum emission of the central part of NGC 253 at the highest resolution, imaged using uniform weighting of the visibilities with the positions of the four sources marked on them. The 15 GHz image was shifted with respect to the source positions in order to align the continuum and line emission from the radio nucleus. Apart from the nucleus, one other line emitting source, which is immediately west of the radio nucleus is seen to spatially coincide with a strong continuum source. This continuum object is not listed in the catalogues of Ulvestad & Antonucci (1997). This H92 α line source also has a H75 α line emission counterpart, which can be seen in figure 3.9a. The other two H92 α sources do not have obvious continuum counterparts, though a continuum image at a much higher resolution might resolve possible counterparts. Note, however, that there exists a slight indentation in the contours of continuum emission at the positions of the two line emitting sources, thus not precluding possible associated continuum sources.



(a) Integrated H92 α line emission from the 15 pc region

(b) The positions of the line sources in the 15 pc region overlaid on a high resolution image of continuum emission

Figure 3.13: **(a).** High resolution integrated H92 α line emission from the 15 pc region, summed over velocities 316.6 to 90.8 km s⁻¹. Line emission which is stronger than the 1 σ value of 0.14 mJy.beam in each channel is used to construct this image. The synthesized beam is 0.38'' $\times$ 0.20'' at a P.A. of -2° . The contour levels are (1, 1.4, 1.8, 2.2, 2.6, 3, 3.4, 3.8, 4.2, 4.6, 5) times 10³ Jy/beam $\times$ Hz. The 'star' symbols mark the derived positions of the four line sources, as listed in table 3.8 and the source numbers identifying the sources are also marked next to the symbols. **(b).** The positions of the four H92 α sources are marked as 'star symbols' on the contours of 15 GHz continuum emission imaged at high resolution. The 15 GHz continuum image is aligned such that the radio nucleus coincides with the position of the H92 α line emission from the source. The synthesized beam of the continuum image is 0.22'' $\times$ 0.10'' at a P.A. of -15° .

The observed differences between the H92 α line channel images of different resolutions could arise due to several reasons. In order to determine whether any extended line emission is resolved out in the higher resolution channel images, the total line flux density within the entire 15 pc sized line emitting region was calculated for line cubes of different resolutions for each of the channels. Based on the results and the noise in the channel images, the data is consistent with no statistically significant amount of line emission which is resolved out in the higher resolution images. Hence, any diffuse line emission in these images, in addition to the four identified compact sources, is consistent with zero and differences in the channel images can be attributed to decreased signal to noise.

The H92 α lines towards the peak positions of the second, third and the fourth sources in the ‘15 pc region’, as listed in table 3.7, are shown in figure 3.14. Line parameters are calculated based on these spectra and are summarised in table 3.9. Since these are not deconvolved line profiles, each of the spectra shown will have contributions from the emission by the other sources. The spectrum of the first source is not shown due to spurious features in the low velocity side. However, identifying the feature near 200 km s⁻¹ as the H92 α line, the integrated line flux for this source is obtained as $\sim 2 \times 10^{-23}$ W m⁻².

Based on table 3.9, the sum of the line emission from the four sources is estimated to be $(18 \pm 1) \times 10^{-23}$ W m⁻². Comparing with the line emission from the entire ‘15 pc region’ of $(20 \pm 2) \times 10^{-23}$ W m⁻², the contributions from other sources to the line emission of a given source, as well as any residual diffuse emission, are consistent with zero. Hence all of the extended emission observed within the 15 pc region can indeed be decomposed fully into four compact sources which are spatially marginally resolved from each other.

Table 3.9: Parameters for the sources in the ‘15 pc region’

Source name	Peak line flux density (mJy/beam)	Central velocity ^a (km s ⁻¹)	FWHM ^b (km s ⁻¹)	Integrated flux ($\times 10^{-23}$ W m ⁻²)		Continuum ^c (mJy/beam)	
				H92 α	H75 α	8.3 GHz	15 GHz
source 1 ^d	0.5 ± 0.1	~ 220	~ 150	~ 2	< 9.1	10.5	9.5
source 2	0.6 ± 0.1	180 ± 10	220 ± 20	3.9 ± 0.4	< 9.1	30	26
source 3	0.75 ± 0.06	200 ± 10	240 ± 22	5.1 ± 0.9	20 ± 3	34	35
source 4	1.15 ± 0.06	192 ± 6	198 ± 13	6.7 ± 0.5	23 ± 3	64	59

^aHeliocentric velocity, optical definition.

^bNo corrections for hanning smoothing or finite resolution have been made.

^cContinuum flux per synthesized beam measured at the position of the line emission.

^dThe H92 α spectrum of source 1 has spurious features at low velocities and hence the estimated line parameters are uncertain.

To summarise, the H92 α line emission is seen towards four compact sources west of the nuclear region and a contiguous extended emission is also seen in a 15 pc sized region around the radio nucleus. The four compact sources will be referred to as the extra-nuclear sources. Three of these sources can be identified with specific continuum counterparts. The line emission in the 15 pc region can be decomposed into four more spatially unresolved sources, which are marginally resolved from each other. Two of these sources have continuum counterparts, one of them being the radio nucleus. The spatial positions and line parameters of the four extranuclear sources as well as the four sources in the 15 pc region have been derived.

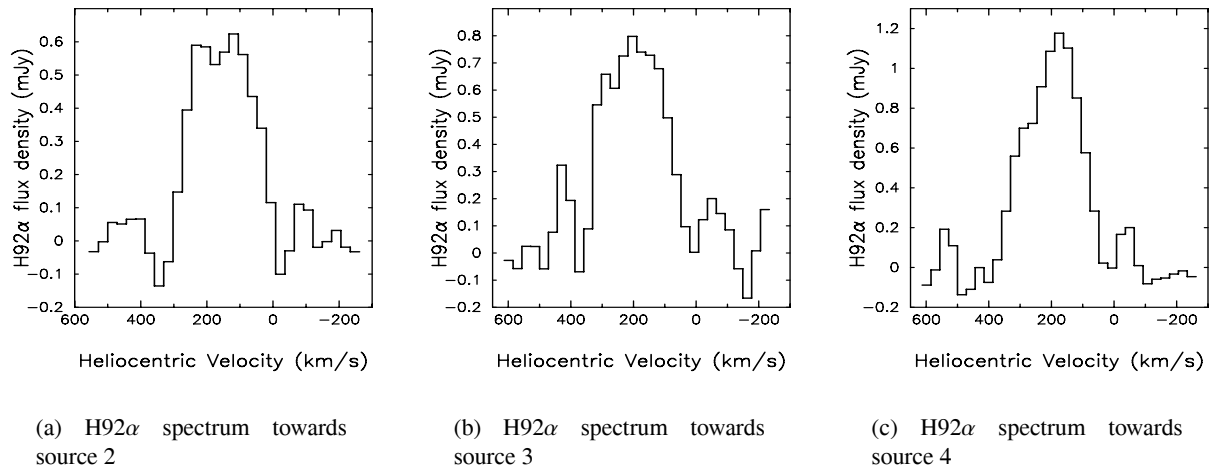


Figure 3.14: The H92 α spectra towards three of the line emitting sources in the 15 pc region. These spectra are obtained towards the pixel whose position coincides with the derived position of these sources and listed in table 3.8. The synthesized beam is $0.51'' \times 0.28''$ at a P.A. of -2° . The rms noise in the channel images is 0.12 mJy/beam.

3.4.3 Properties of the ionized gas

Low resolution data on large scale RRL emission at 4.8 GHz and 8.3 GHz (Anantharamaiah & Goss, 1990) as well as 99 GHz line emission obtained with a single dish (Puxley et al., 1997) are available in the literature. We use these, along with our 1.4 GHz, 8.3 GHz and 15 GHz recombination line data to model the ionized gas in NGC 253. In section 3.4.3.1, the large scale multi-line emission observed with low resolution is modelled in terms of a single component of ionized gas. In section 3.4.3.2, the four extra-nuclear sources are modelled individually and in section 3.4.3.3, the properties of the four line sources identified in the 15 pc region are derived. Section 3.4.3.4 deals with the 1.4 GHz line emission in which a model of the ionized gas in NGC 253 consistent with all of the available line data is derived.

3.4.3.1 Large scale emission

The H40 α line at 99 GHz was observed by Puxley et al. (1997) using the single dish Nobeyama Radio Observatory with a beam of $17''$ and they quote the integrated line flux, corrected assuming a line emitting region of size $7''$, to be $6.3 \times 10^{-20} \text{ W m}^{-2}$. They also plot the low resolution RRL data for this galaxy from 1.4 GHz up to 99 GHz and show that the slope of F_ν ($= \int S_\nu d\nu$) versus frequency ν is very close to 2.0, i.e., $F_\nu \sim \nu^2$. The theoretically expected dependence of F_ν on frequency when $\tau_c \ll 1$, $|\tau_l| \ll 1$, assuming LTE conditions and neglecting pressure broadening, is ν^2 . Puxley et al. (1997) also note that the 1.4 GHz line measurement lies above the best fit line, which they attribute to an additional component to the total line emission due to stimulated emission by the background which would be more intense at low frequencies. However, our revised measurement of the 1.4 GHz H166 α line flux is much lower than that given in Anantharamaiah & Goss (1990) and this new value can be seen to lie exactly on the best fit line. The revised 1.4 GHz line data, the 4.8 GHz and 8.3 GHz line measurements from Anantharamaiah & Goss (1990) and the H99 α line at 99 GHz are plotted in figure 3.15. A function of the form $F_\nu \propto \nu^\alpha$ is fit to the data. The best fit value of α is obtained to be 1.93 ± 0.04 and

this best fit line is also plotted in the figure. As can be seen from the fit, the data over a wide range of frequencies can be described well by a ν^2 law.

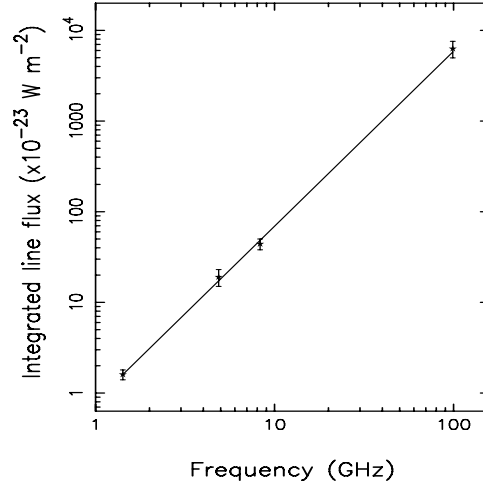


Figure 3.15: The low resolution integrated line flux *vs.* frequency for NGC 253. The data points are marked with errorbars and the solid line is the best linear fit through the data. The 1.4 GHz data is from our work, the 4.8 GHz and 8.3 GHz data is from Anantharamaiah & Goss (1990) and the 99 GHz data is from Puxley et al. (1997). The values of the plotted line fluxes are $(1.6 \pm 0.2) \times 10^{-23} \text{ W m}^{-2}$, $(1.9 \pm 0.4) \times 10^{-22} \text{ W m}^{-2}$, $(4.4 \pm 0.6) \times 10^{-22} \text{ W m}^{-2}$ and $(6 \pm 1) \times 10^{-20} \text{ W m}^{-2}$ respectively.

The obvious explanation, as discussed in Puxley et al. (1997), is that all of the RRL emissions from 1.4 GHz up to 99 GHz, arise in gas which is optically thin and also pressure broadening is negligible compared to the doppler widths. This result is surprising since we do not expect LTE conditions and also optical thinness to hold over all frequencies. Though the observed ν^2 relation and the implications derived above seem to be rather stringent constraints on the gas properties, it must also be noted that if the integrated flux at 1.4 GHz is changed by factor of two, the spectral index between 1.4 GHz and 99 GHz changes by 0.16. Hence it is possible, for example, to construct a two density model where one density component is optically thin even at 1.4 GHz and the other is optically thick at 1.4 GHz but becomes thin at higher frequencies, and are comparable in the ionization required.

Shown in figure 3.16 are the theoretical contours of the spectral index α between 1.4 GHz and 99 GHz as a function of electron density and emission measure EM, with pressure broadening included, for LTE as well as for non-LTE. In the LTE case, it is seen that the spectral index α is essentially a function of EM, i.e., τ_c , and is very close to 2.0 for EM less than 10^6 pc cm^{-6} (or τ_c at 1.4 GHz < 0.4). α increases for increasing values of $\text{EM} > 10^6 \text{ pc cm}^{-6}$ since the H166 α line flux decreases dramatically as the gas becomes optically thick. The value of α can be seen to depend weakly on the value of density for low EM due to the effects of pressure broadening. However, the behaviour of α is very different when non-LTE effects are also included. The value of α is ~ 2.0 for low values of EM but there exists two regions in the density-EM plane where the optical depths are large, and α is close to 2.0. The ratio between the non-LTE line flux and the LTE line flux is given by $1/b_n$ for optically thin regimes and is hence close to unity with a weak density dependence. Therefore, if the observed value of α is close to 2.0 then an LTE analysis (as is carried out by Puxley et al. 1997) is a good approximation. However, when the optical depth is large and the gas occupies the region of density-EM space where α is 2.0

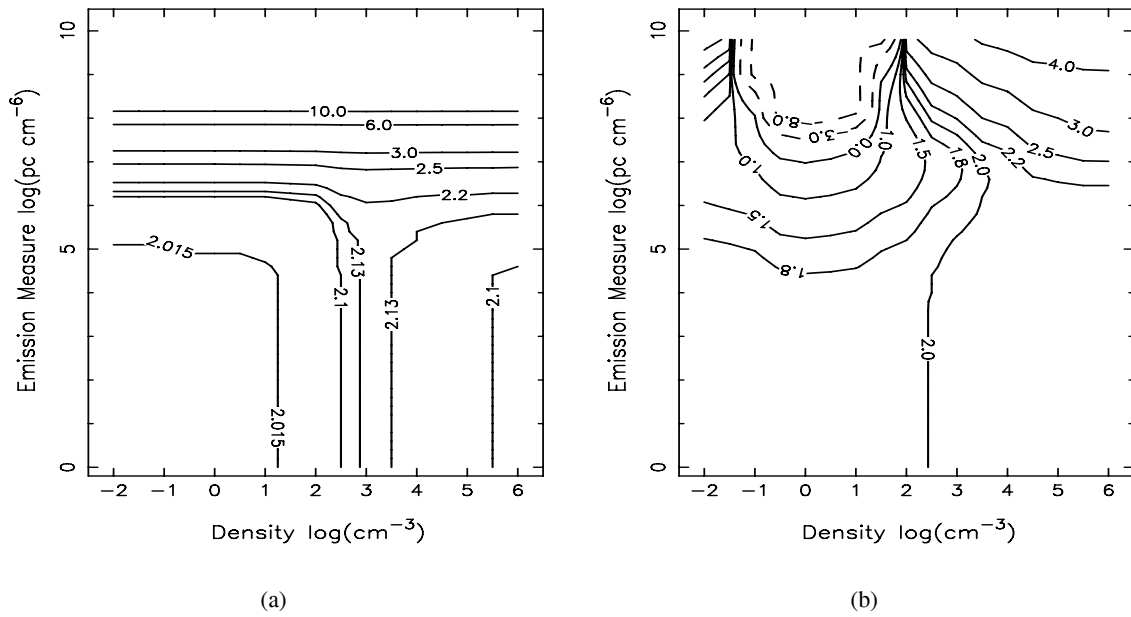


Figure 3.16: The expected dependence of the spectral index between the 1.4 GHz H166 α and the 99 GHz H40 α line fluxes as a function of density and emission measure under **(a)**. LTE conditions and **(b)**. non-LTE conditions.

in the non-LTE case, then the ratio of the non-LTE to LTE line flux can be arbitrarily large for lower frequencies and hence an LTE analysis is invalid in general. Additionally, though the line flux measurements fall on a ν^2 relation, it remains to be seen, even if LTE and optical thinness is assumed, whether the resultant solutions are consistent with other constraints like the total continuum emission and the size of the line emitting region.

Therefore, in the remaining part of this section, we model the multi-line data to determine whether all of the line emissions from 1.4 GHz up to 99 GHz can indeed be explained as arising from a single component of gas. We first model the spectral indices, that is, the model is constrained only by the observed spectral indices and not by the actual measurement values. Next, we include in the model, the actual values of the line fluxes and also the observed size of the line emitting region in NGC 253. The final model considered is constrained to produce only the cm-wave RRLs and not the H40 α line in order to determine whether a two-component model of the ionized gas is more appropriate for the ionized gas.

We first model the multi-frequency data plotted in figure 3.15 as arising from ionized gas at a fixed density in order to investigate the behaviour of the spectral index of the line flux. The ionized gas is assumed to be in the form of a rectangular slab and at a temperature of 5000 K. The free parameters are the density n_e , the lateral extent L and the thickness l of the slab. For each combination of input parameters, the 1.4 GHz, 4.8 GHz, 8.3 GHz and 99 GHz integrated line fluxes, normalised to the 1.4 GHz values, are calculated, including the effects of pressure broadening. These line fluxes are then fit with the function $F_\nu \propto \nu^\alpha$ with the errors in these values computed by assuming the same fractional error as in the observed values, listed in the caption of figure 3.15. If the fitted value of α is within 1σ of the value of α derived from the actual measurements (1.93 ± 0.04), then the solution is accepted as valid. Therefore the only constraint imposed in the model is that of the spectral index of the line fluxes and not their absolute values. The solution space in the density-EM plane is mostly confined to

$n_e \leq 100 \text{ cm}^{-3}$ and $EM \leq 10^4$ with some isolated high density solutions as well ($n_e = 10^3 \text{ cm}^{-3}$ and $EM = 10^6 - 10^7 \text{ pc cm}^{-6}$; $n_e = 5 \times 10^4 \text{ cm}^{-3}$ and $EM < 10^5 \text{ pc cm}^{-6}$). Higher density solutions for low values of EM were disallowed partly due to the effects of pressure broadening. The doppler width is assumed to have two components; thermal broadening corresponding to $T_e = 5000 \text{ K}$ and also turbulent broadening due to a root mean square velocity dispersion of 10 km s^{-1} . If therefore, the intrinsic doppler width is much larger due to large scale motions of the gas along each line of sight, then the effects of pressure broadening would become far less significant, thus making possible higher density solutions for $EM \leq 10^4 \text{ pc cm}^{-6}$ as well. However, the required velocity width along a line of sight to increase the range of allowed densities is much larger than what is observed in galaxies and is hence not feasible. For purely LTE line emission, no solution was obtained for the spectral index of the model less than 2σ off from the measured value. If the spectral index is allowed to depart by more than 2σ from the measured value for LTE emission, then the solution space derived is $n_e < 50 \text{ cm}^{-3}$ and $EM \leq 10^5 \text{ pc cm}^{-6}$.

In the second model, the gas in form of a uniform slab, assumed to emit all of the observed line fluxes at the four frequencies, is now constrained to produce the measured values of the integrated line fluxes as well, within 2σ errors. On the other hand, the procedure described in the previous paragraph models only the spectral indices of the line emission (or equivalently, the line ratios). The four line measurements are indeed satisfied by a range of input parameters. The values of the lateral angular extent L obtained, however, are rather large. The minimum L for $T_e = 5000 \text{ K}$ is $10''$ and occurs for a density of 1000 cm^{-3} . However, it is known that the line emitting region is much smaller than this. Low resolution observations imply that the size of the emitting region is between $5-7''$ (Anantharamaiah & Goss, 1990, 1996; Puxley et al., 1997) and high resolution observations presented here indicate that the total size of the various resolved emitting regions is probably even less. Also, the minimum value of the thermal continuum at 99 GHz predicted by the model is 250 mJy for $T_e = 5000 \text{ K}$ and even higher for 7500 K. Carlstrom (1990) measured a value of $350 \pm 50 \text{ mJy}$ for the 99 GHz continuum flux density and Peng et al. (1996) measured a value of $320 \pm 30 \text{ mJy}$. Peng et al. (1996) suggest, based on a decomposition of the continuum spectrum, that about a fourth of this flux density is due to free-free emission, a fourth due to non-thermal emission and the remaining half, due to dust emission. Even if half the total observed continuum is assumed to be due to free-free emission, this implies that the model solutions violate this continuum constraint. Therefore we conclude that all of the line emissions at the four frequencies cannot be explained by a single density ionized gas model, even though the spectral index of the line flux indicates a simple optically thin scenario.

Anantharamaiah et al. (2000) have modelled the ionized gas in Arp 220 using RRL data from 1.4 GHz up to 207 GHz and show that the cm-wave RRLs and mm-wave RRLs arise in two distinct components of ionized gas. Motivated by this, we model the RRL data for NGC 253 again, and attempt to explain the 1.4 GHz, 4.8 GHz and the 8.3 GHz lines as arising from gas at a single density. The $H40\alpha$ line measurement is used only as an upper limit. Valid solutions are indeed obtained in this case. The results of Models II and III are fairly similar. The gas density ranges between $400-1000 \text{ cm}^{-3}$ with an effective size of $\sim 35 \text{ pc}$. The ionization rate is close to $8 \times 10^{52} \text{ s}^{-1}$. Only 10-20 % of the observed $H40\alpha$ line flux is produced by this component of gas. The rest of the high frequency emission presumably arises in gas at a much higher density. The size of the $H92\alpha$ line emission region in the high resolution images presented in this work is consistent with the derived value of $\sim 35 \text{ pc}$.

Hence, we have shown that the line flux spectral indices alone (i.e., the line ratios), from 1.4 GHz up to 99 GHz, can be explained in a single model of ionized gas, as in Puxley et al. (1997). However, inclusion of the actual values of line fluxes along with the physical parameters of NGC 253 shows that this is not possible. Hence all of the RRL emission from 1.4 GHz up to 99 GHz cannot arise in the same component of ionized gas. However, ionized gas at a fixed density can be modelled to produce all of the cm-wave RRLs but only a fraction of the mm-wave RRLs. That consistent solutions can be derived which can explain all of the 1.4 GHz, 4.8 GHz and 8.3 GHz line emissions does not necessarily imply that these lines do indeed originate from ionized gas with these properties. The morphology of the line emission in the H92 α line images is seen to be complicated and consists of individual sources, which may have widely different properties. Hence the values derived in the exercise described above could be meaningless averages over these properties. For example, as described in the previous section, the line emission from the radio nucleus arises in gas at a density 10 times higher than the derived value of 10^3 cm^{-3} and contributes about 10 % of the total ionization derived here. Therefore each of the compact line emitting sources need to be modelled separately, as will be done in the following two sections.

3.4.3.2 Extranuclear compact sources

In the previous section, the entire large scale line emission was modelled as arising from gas of a given density and size. By doing so, small scale homogeneities in gas properties are averaged over, with a complicated weighting function. Also, since the total size of the line emission is large, the thermal gas probably has an area filling factor much less than unity, thus making the constraint of the maximum possible size less meaningful (see section 2.3 for a detailed discussion). Higher resolution RRL data at 8.3 GHz and 15 GHz obtained by us resolve individual line emitting regions and the properties of these regions can be modelled separately. At 8.3 GHz, we have identified five main regions of line emission: four distinct compact objects which may or may not be physically associated with a radio continuum source, and the more complex 15 pc region which has been decomposed into four compact sources. In this section, the emission from the four extranuclear sources are modelled in order to derive the properties of each source. We refer to the line sources by the names of nearest continuum sources which may or may not be their actual counterparts. The RRL models for these sources are constrained to produce the observed H92 α line flux and the upper limit to the H75 α line flux (3σ upper limit being $7.2 \times 10^{-23} \text{ W m}^2$), which are summarised in table 3.7. The free-free emissions at 8.3 GHz and 15 GHz are also constrained to be less than the total continuum fluxes measured at position of the line emission. Since all four sources are spatially unresolved, the thermal gas is further constrained to have a lateral angular size $< 0.35''$.

(1) 5.49–42.3: UA97 derive the spectral index of this continuum source between 8.3 GHz and 23 GHz to be -0.28 ± 0.36 . This implies that the continuum emission has a significant thermal fraction, supporting the identification of the line emitting source with 5.49–42.3. The H92 α line spectrum is shown in figure 3.7a. The 8.3 GHz continuum flux density of the sources is 1.12 mJy (UA97) and the 15 GHz value is estimated to be 1.0 mJy using the spectral index of -0.28 . No solutions are obtained for Model I (single spherical HII region). The required optical depth and hence the transverse size L do not allow for a spherical model. Using Models II and II, the gas density is derived to be between $4000\text{--}10000 \text{ cm}^{-3}$. Uniform slab model

solutions obtained correspond to thin slabs: the allowed values of L and l are 2-3.5 pc and 0.01-0.04 pc respectively. The ionization rate is constrained to be close to $1 \times 10^{51} \text{ s}^{-1}$ and the total mass of ionized gas ranges between 160-360 $M_{\odot}$. These solutions are obtained for values of stimulated emission ranging from almost zero to almost 100 %. Since the association of the line emission with the continuum source is not confirmed, the continuum upper limits assumed in the modelling could be in error. However, a more weakened constraint in the form of continuum flux upper limits which are twice that assumed, does not change the model solutions significantly. In order to explain the derived ionization rate, about 75 O stars are required (using the tabulated numbers given in Vacca, Garmany, & Shull 1996). For a Salpeter IMF with a lower mass cutoff of 1 $M_{\odot}$, the total stellar mass is $1.4 \times 10^4 M_{\odot}$. The $H\alpha$ emission is calculated to be $2 \times 10^{-15} \text{ W m}^{-2}$. Forbes et al. (2000) have measured the $H\alpha$ fluxes of emission knots in NGC 253 but their list does not cover this region of the galaxy. However, if 5.49–42.3 were not to dominate the $H\alpha$ image, the (foreground) extinction towards this object must exceed 10 magnitudes.

(2) 5.59–41.6 (= IR peak?): This line emitting object is seen to be the most prominent source following the 25 pc region, in the lower resolution H92 α image of Anantharamaiah & Goss (1996). The high resolution H92 α line emission is spatially unresolved and the spectrum is shown in figure 3.7b. The peak continuum flux of the continuum source at 8.3 GHz and 15 GHz are estimated to be 3.1 mJy/beam and 5.8 mJy/beam respectively. Models I, II and III are used to model the ionized gas in this source. The derived gas density ranges between 2000-20000 cm^{-3} and the ionization rate varies between $(1-3) \times 10^{51} \text{ s}^{-1}$. The size of the thermal gas is 1-5 pc. Though the line flux of this source and hence the ionized gas properties are similar to those of the other three compact sources discussed here, 5.59–41.6 is potentially an interesting object. The infrared/optical continuum and line emission from NGC 253 is dominated by a single compact source, referred to as the IR peak. The radio continuum image, on the other hand, consists of a linear chain of a number of compact sources. The brightest radio source is of course the radio nucleus. It has been shown (by Piña et al. 1992, Sams et al. 1994 and others) that the radio nucleus and the IR peak are two distinct objects, spatially well separated. Based on their astrometry, the radio continuum sources closest to the position of the IR peak are 5.59–41.6 and 5.62–41.3 and of these, the former is closer. Due to errors in the relative astrometry of the radio and infrared reference frames, it is not possible to unambiguously identify associated infrared emission with the radio nucleus or associated radio emission with the IR peak. The NIR, MIR, Bry and [NeII] images show a secondary weak infrared source northeast of the IR peak which has sometimes been identified with the radio nucleus. The separation between the two infrared continuum peaks is 2.7'' in R.A. and 1.7'' in Dec (Keto et al., 1993, 1999) and is 2.5'' in R.A. and 2.1'' in Dec for the Bry peaks. The separation between the radio nucleus and the continuum source 5.59–41.6, as is that between the associated recombination line emission peaks, is 3.0'' in R.A. and 2.5'' in Dec. Hence it is not possible to simultaneously identify the radio nucleus and 5.59–41.6 with the two infrared sources, as was also argued by Kalas & Wynn-Williams (1994), Böker et al. (1998) and Forbes et al. (2000). However, most models of the IR continuum and line emission from the IR peak indicate that the free-free emission from the ionized gas must be 5-10 mJy. Therefore, if neither of the two radio sources are the counterparts of the IR peak, it is difficult to explain the absence of an additional strong radio continuum source at the offset position of the IR peak. The neighbouring radio continuum source, 5.62–41.3, however, is

offset by 2.55'' in R.A. and 2.2'' in Dec from the radio nucleus. Hence, by assuming a non-zero astrometric error between the radio and infrared images, it may be possible to associate the radio nucleus and 5.62–41.3 with the infrared sources. The radio spectral indices of 5.62–41.3 and 5.59–41.6 are -0.21 ± 0.14 and $+0.61 \pm 0.15$ respectively. Hence both these sources possess significant amounts of thermal emission and are possible candidates for the radio counterpart of the IR source. However, the detection of recombination lines from 5.59–41.6 leads us to suggest that this is indeed the IR peak. Based on the RRL models, the ionization rate is derived to be $\sim 2 \times 10^{51} \text{ s}^{-1}$. This value cannot be directly compared with either that derived by Keto et al. (1999) of $4 \times 10^{52} \text{ s}^{-1}$ based on [NeII] emission (since this line emission seems to bear little resemblance to the RRL emission) or to that derived by Forbes et al. (1993) of 1.6×10^{51} based on Bry emission, since the latter is measured over a 2'' aperture and is also affected by dust extinction. The question as to why the IR peak dominates the infrared continuum and line emission but is comparable in recombination line emission to the other sources in the galaxy is discussed in greater detail in section 3.3.4.

(3) *5.72–40.1*: 5.72–40.1 was identified by UA97 as the brightest thermal source in NGC 253 and it exhibits a flat spectral index from 4.8 GHz up to 23 GHz. Hence we associate the line emission with this HII region. The H92 α line spectrum is shown in figure 3.7c. UA97 derived the properties of this object using their continuum data. This source was found to have a size of 2.4 $\times$ 1.2 pc, an ionization rate exceeding $5 \times 10^{51} \text{ s}^{-1}$, and an rms density of $\sim 10^4 \text{ cm}^{-3}$. The total mass of ionized gas is about 570 $M_{\odot}$ and the continuum optical depth at 8.3 GHz was estimated by UA97 to be 0.7. We model the properties of the H92 α emitting ionized gas in this object using the continuum constraints from UA97. The solutions obtained are for gas densities between 2000 and 10000 cm^{-3} which require an ionization rate between 10^{51} – 10^{52} s^{-1} . The single HII region solutions obtained in Model I have diameters between 1.4–2.7 pc and a ionized gas mass between 350–1300 $M_{\odot}$, similar to what was derived by UA97. Though the derived gas properties described above are common to Models I, II and III, a uniform slab of density 1000 cm^{-3} with a lateral extent between 4–15 pc and a thickness of 0.3–1 pc is also consistent with the observations. The fraction of the observed 8.3 GHz continuum of 6.5 mJy which is due to free-free emission is calculated to be 0.1 or even less. However, UA97 derive a flat spectral index from 4.8 GHz up to 23 GHz and hence attribute all of the observed continuum to free-free emission. Therefore we model the ionized gas again, such that the 8.3 GHz, 15 GHz and 23 GHz free-free emission is constrained to be within 10 % of the values obtained by UA97. The conditions on the recombination line emission are as before, but the component of the line emission due to stimulated emission by an external background is made zero. Only models II and III yield solutions consistent with the imposed constraints. The resultant densities range from 5000–40000 cm^{-3} and the ionization rate is between $(5\text{--}6) \times 10^{51} \text{ s}^{-1}$. The 4.8 GHz thermal continuum emission, however, is significantly less than the observed value of 7.7 mJy and hence all of the observed continuum emission from this source cannot be free-free emission from gas at a single density. An ionization rate of 6×10^{51} corresponds to 450 O stars and a total stellar mass (for a Salpeter IMF and a lower mass limit of 1 $M_{\odot}$) of $8.5 \times 10^4 M_{\odot}$. The H α flux is estimated to be $1.2 \times 10^{-14} \text{ W m}^{-2}$. Forbes et al. (2000) have tabulated the line fluxes of the H α knots in NGC 253. The H α source nearest in position to 5.72–40.1 is 33 $^{\circ}$.14; 18.1'' (J2000.0), which, according to their astrometry, is $\sim 0.4''$ east of our radio source and has a line flux of $8 \times 10^{-19} \text{ W m}^{-2}$. Hence, if this H α knot is indeed associated with 5.72–40.1, then it has a

(foreground) extinction of 13 magnitudes.

(4) 5.75–39.9: This is the only extranuclear H92 α emission source with no obvious continuum counterpart and hence the association of this line emission with the source 5.75–39.9 is possibly not real. The H92 α line spectrum is shown in figure 3.7d. The peak 8.3 GHz continuum flux at the position of the peak line emission is 5.5 mJy/beam in the uniform weighted image. Inspection of the uniform weighted 15 GHz continuum image indicates that the line emission seems to lie in a region of minimum continuum emission and is in fact surrounded by strong continuum sources. Based on the continuum fluxes of neighbouring sources, we assume that the total free-free continuum flux density from the line emitting gas should not exceed 5.5 mJy at both 8.3 GHz and at 15 GHz. Given these uncertainties in the continuum measurements, the component of line emission due to externally stimulated emission is assumed to be zero in the models. The derived density ranges between 2000–10000 cm⁻³ with an ionization rate of (2–5)×10⁵¹ s⁻¹ and gas mass greater than 1000 M_⊙. The predicted free-free continuum at 8.3 GHz and 15 GHz are >2 mJy and >2.5 mJy respectively. No H α or IR emission knots are seen in this region (Forbes et al., 2000) and hence the ionized gas must be obscured with extinction exceeding 9 magnitudes.

The ionizing source for these compact and isolated HII regions would have to be a star cluster. Based on the derived ionization rates, the number of O stars required for the sources 5.49–42.3, 5.59–41.6, 5.72–40.1 and 5.75–39.9 is 75, 150, 450 and 150–450 respectively. The former two would therefore be classified as massive clusters whereas the latter would fall in the category of SSCs. The stellar masses, assuming a Salpeter IMF and a lower mass cut-off of 1 M_⊙ range between (1.5–8.5)×10⁴ M_⊙ for these clusters. The widths of the H92 α lines from all four sources (see table 3.7) are supersonic. Since the line emission from these objects is unresolved, the size of each HII region is less than ~4 pc. Therefore, the dynamical age of these nebulae ranges between (4–10)×10⁴ years. The lower end of this range is too short an age for a cluster possessing a number of fully formed O stars. A cluster whose age is at the higher end of this range, though, is feasible. This problem is of course reminiscent of NGC 5253, He 2–10 and the radio nucleus of NGC 253. High resolution H92 α observations, therefore, seem to detect such compact dense HII regions with supersonic line widths extremely easily. However, it is not obvious as to why this line emission is not detected from dense compact HII regions with subsonic line widths. It is tempting to conclude that such objects, if powered by SSCs, do not exist.

3.4.3.3 ‘15 pc region’

The ‘15 pc region’ consists of H92 α line emission from four distinct sources, marginally resolved from each other. Since the line and continuum parameters have been derived for each of these sources, they can be modelled individually in order to extract the physical properties of the gas. However, in order to illustrate the effect of the angular size constraint and hence of higher resolution, we first model the entire emission from the 15 pc region as a uniform slab of ionized gas. This gas is constrained to produce all of the observed H92 α line emission as well as the entire 1.4 GHz RRL emission, since the four extranuclear sources account for much less than 10 % of the observed 1.4 GHz RRL flux. The 1.4 GHz line emission is assumed to arise within the 15 pc region. The H40 α observation is imposed as an upper limit. The total continuum flux density is measured to be 150 mJy both at 8.3 GHz as well as 15 GHz. A peak 1.4 GHz

continuum flux of 120 mJy is used in this model, based on the high resolution ($1.7'' \times 0.94''$) image of UA97 and the total 99 GHz flux density is assumed to be 75 mJy. In this model, the gas density is derived to be $600\text{--}3000\text{ cm}^{-3}$ and the ionization rate is $\sim 10^{52}\text{ s}^{-1}$. At least 85 % of the H92 α line emission is due to stimulated emission by the background non-thermal radiation. The effective size is 14 pc and less, and hence the area filling factor can be as high as unity. The contribution by this gas component to the observed H40 α line flux is less than a few percent.

The maximum angular size of the line emitting region is an effective constraint in RRL modelling. The multi-frequency continuum and line ratios determine the range of allowed emission measures through optical depth effects and hence the total line emission determines the transverse size of the thermal gas. Therefore we model the ionized gas in each of the four sources within the ‘15 pc region’ and compare with those obtained by modelling the region as a whole (as described above). The H92 α fluxes of the four sources are listed in table 3.9. The recombination line object named ‘source 4’ is the same as the radio nucleus and the line emission from this object has been modelled in detail in section 3.3. The H75 α line is detected in two of the sources (the radio nucleus and ‘source 3’). The 3σ upper limits to the 15 GHz line are calculated for the other two sources for a line width equal to that of the H92 α line. The upper limits to the 8.3 GHz free-free emission from these objects are given by the continuum emission measured at the position of the H92 α line peak over one synthesized beam. The corresponding 15 GHz constraint is estimated from the 15 GHz continuum image convolved to the resolution of the 8.3 GHz image. These values are listed in table 3.9 and correspond to one synthesized beam area of size $\sim 0.5''$ or $\sim 6\text{ pc}$. Since the maximum value of the size of the thermal gas is quite small, we model the ionized gas as a single spherical HII region as well as an uniform slab and the width of the line profile used in calculating the line optical depth is assumed to be the observed H92 α line width itself. Though the continuum emission between 8.3 GHz and 15 GHz for the four sources is flat and is hence consistent with optically thin free-free emission, the entire observed emission need not arise in the line emitting gas. Hence in Model I, the ‘deabsorbed’ continuum is assumed to be behind as well as in front of the thermal gas whereas in Model II, is assumed to be fully behind the thermal gas. The solutions obtained from the different models for each source are similar and are described in table 3.10. The gas densities of sources 3 and 4 are well constrained to a narrow range using the line measurements at 8.3 GHz and 15 GHz. However, since only an upper limit for the 15 GHz line flux is available for sources 1 and 2, a wider range of densities are consistent with the available data and typical low density as well as high density solutions are listed for these objects in the table. The spectral indices of the line fluxes are also listed and values very different from 2.0 are obtained.

The gas properties of the four compact sources within the ‘15 pc region’ are similar to each other, as can be seen from the table. However, these do not agree with the solutions derived by modelling the entire region as a whole, as described earlier in this section. The H92 α flux measured over the 15 pc region is, within errors, equal to the sum of the contributions from the individual sources. Hence the main difference between the two models, leading to differing gas properties, is the stricter constraint on the maximum transverse size of the line emitting gas in the latter case. The ionization rate obtained for the four sources is between $(1.8\text{--}3.8) \times 10^{52}\text{ s}^{-1}$, a factor of 2–4 higher than that derived for the whole region. The derived gas densities are also consistently higher for the individual sources, and so are the optical depths. Also, models for the entire region require an external stimulated emission component of greater than

85 % at 8.3 GHz whereas the four individual sources can be modelled even with zero external stimulated emission, but with slightly larger gas masses and sizes. The predicted continuum and line emissions at 1.4 GHz, 8.3 GHz and 99 GHz are listed in table 3.10. Except for a class of low density solutions for source 2, all other model solutions for these objects imply a negligible contribution to the observed 1.4 GHz line flux from the sources in the 15 pc region. Even if the low density model were true for source 2, not more than 20 % of the H166 α line can be accounted for by these sources.

Table 3.10: Model results for the four sources in the ‘15 pc region’

Parameter	Source 1 ^a		Source 2 ^a		Source 3	Source 4
	Low	High	Low	High		
Density ($\times 10^3 \text{ cm}^{-3}$)	2	10	0.9	6	8-10	7-10
Effective size (pc)	5	1.8	6.4	2.6-3.7	2-2.5	2.5
τ_c at 8.3 GHz	0.2	1.7	0.05	0.8	1-2.5	1-2
S_{ff} at 8.3 GHz (mJy)	0.4	0.3	2	4	6	5.5
N_{Lyc} ($\times 10^{51} \text{ ph. s}^{-1}$)	2.5-5	4-5	1.5	4	8-15	6-14
Mass ($\times 10^3 M_{\odot}$)	3-5	0.8	3.2	1.3	1.5-2.5	1.3-2
1.4 GHz line flux/observed (%)	1	0.05	19	0.1	0.05	0.05
1.4-8.3 GHz line spectral index	2.7	4.6	1.4	4.3	4.8	4.8
4.8 GHz free-free flux density (mJy)	3-5	1.6	1.2	3-5	2.7	2.5-5
4.8 GHz line flux/observed (%)	5	1.6	13	5	3.5	5
99 GHz free-free flux density (mJy)	2.3-4.3	4	1.8	2-7	6-10	6-12
99 GHz line flux/observed (%)	0.8	1.1	0.3	1	2.5	2.5
99-8.3 GHz line spectral index	1.3	1.4	0.7	1.1	1.3	1.3

^aFor sources 1 and 2, the density range is large; typical low and high density solutions are listed.

3.4.3.4 Modelling the 1.4 GHz line emission: multi-density gas

The high resolution H92 α line data has been modelled in terms of 8 compact sources in the previous two sections. The derived gas densities for these sources lie between few 1000 to few 10000 cm^{-3} , corresponding to compact HII region densities in the Galaxy. The continuum and line emission of each of the sources at 1.4 GHz, 4.8 GHz and 99 GHz have also been computed. The sum of the predicted fluxes of the 8 high density sources are listed in table 3.11 (as component I) along with the total emission measured using lower resolution data. Of the total H92 α line flux measured by Anantharamaiah & Goss (1990) from their low resolution data, a net flux of $18.8 \times 10^{-23} \text{ W m}^{-2}$ is not detected in our high resolution data and hence this line emission must be spread over a large area such that the flux per A configuration beam of size $\sim 0.37''$ is less than the 3σ limit of $0.6 \times 10^{-23} \text{ W m}^{-2}$ per beam (for a spectrally unresolved line). The eight sources contribute no more than 2.3-21 % of the observed H166 α emission at 1.4 GHz, between 18-36 % of the H110 α emission at 4.8 GHz and about 9 % of the H40 α emission at 99 GHz. Therefore, in order to explain the remaining emission at these frequencies, additional components of ionized gas must exist apart from the line sources detected at 8.3 GHz at high resolution. The remainder of the 1.4 GHz line emission and the 99 GHz line emission cannot be explained by the same component of gas. As in the case of Arp 220 (Anantharamaiah et al., 2000), the high frequency line is emitted by gas at densities larger than 10^4 cm^{-3} and this component produces negligible amounts of lower frequency recombination line emission due to huge continuum optical depths. Hence a minimum of three components of ionized gas seem to be required in order to explain all of the observed RRL data from NGC 253 - one which

explains the high brightness part of the 8.3 GHz line emission seen at high resolution and has been described in detail in the previous sections (Component I), one which explains most of the 1.4 GHz line and the remainder of the 4.8 GHz and 8.3 GHz line (Component II) and a third which primarily explains the mm-wave line (Component III). Since the H40 α line was detected by Puxley et al. (1997) at low signal to noise, the exact value of the line flux is uncertain and hence we do not attempt to model this high frequency line emission. The second component of ionized gas is modelled below. Note that the ionized gas in Arp 220 was also modelled in terms of three components. However, the diffuse low density component (similar to our component II) was constrained by the upper limit to the 1.4 GHz line and the observed low frequency continuum turnover. Since the actual value of the 1.4 GHz line emission is known for NGC 253, the properties of this gas component can be much better constrained in this case.

Component II is modelled assuming that it produces all of the remaining 1.4 GHz, 4.8 GHz and 8.3 GHz line emission. Though it is possible that this component does not account for all of the remaining 8.3 GHz emission, this assumption is the simplest to make and also avoids the need for an additional fourth ill-constrained component of ionized gas. The 99 GHz line constraint is imposed as an upper limit. The maximum size of the line emitting region is taken as 7.5'', which is the size of the low resolution line emissions. The ionized gas is modelled as a uniform slab (Model II) as well as a collection of HII regions (Model III) and the electron temperature is assumed to be 5000 K.

Solutions are obtained for values of the externally stimulated emission component ranging from zero to almost 100 %. Two classes of models are obtained; large l_{eff} and small l_{eff} . The transverse size of the thermal gas in the small l_{eff} model solutions is less than ~ 10 pc, extending down to 0.5 pc, the ionization rate is less than few times 10^{51} s^{-1} and the line emission is dominated by stimulated emission. The transverse size is that of the thermal gas as well as that of the background radiation. Since high resolution images show the continuum emission to be spread over a much larger area, even after accounting for filling factor effects, we rule out these models as implausible. The large l_{eff} models are obtained when the background radiation is assumed to fill almost the entire region of line emission. These yield densities between 300-1000 cm^{-3} , effective sizes between 30-60 pc and ionizing photon rate of $(3-6) \times 10^{52} \text{ s}^{-1}$ and the stimulated emission component is between 50-90 %. The data can also be modelled assuming zero stimulated emission, thus attributing all of the line flux to purely internal emission in the thermal gas. This class of solutions, obtained for a uniform slab model, is for densities between 200-500 cm^{-3} , ionization of $(4-6) \times 10^{52} \text{ s}^{-1}$ and ionized gas mass of $(2-5) \times 10^5 M_{\odot}$. The continuum optical depth is close to unity at 8.3 GHz. Hence the most plausible models for component II are for gas densities of a few 100 cm^{-3} , transverse size of few tens of parsecs and ionization of about $5 \times 10^{52} \text{ s}^{-1}$. This gas contributes about 10-12 % of the remaining 99 GHz emission listed in table 3.11 and hence an additional higher density compact component (III) is obviously necessary.

**Table 3.11: Continuum and line fluxes for NGC 253
for components I, II & III**

Parameter	Predictions for comp. I	Low res. data	Expected for comp.s II & III
H166 α at 1.4 GHz ($\times 10^{-23}$ W m $^{-2}$)	0.03-0.3	1.6	1.5 ± 0.4
H110 α at 4.8 GHz ($\times 10^{-23}$ W m $^{-2}$)	3.4-6.9	19.1	14.5 ± 4
H92 α at 8.3 GHz ($\times 10^{-23}$ W m $^{-2}$)	25.5	44.4	19 ± 3
H40 α at 99 GHz ($\times 10^{-23}$ W m $^{-2}$)	564	6270	5706
1.4 GHz continuum (mJy)	10	852	<842
4.8 GHz continuum (mJy)	11-27	1000	<990
8.3 GHz continuum (mJy)	25	800	<775
99 GHz continuum (mJy)	23-42	75	<52

Col (1): Parameter; col (2): sum over the eight sources of the predicted values of the parameter; col (3): total value of parameter from low resolution data; col (4): the difference between col. 3 and col. 2, which is the expected value for components II and III together.

3.4.4 Discussion

The continuum spectral index measurements by UA97 indicate that thermal gas is present over a substantial area and also forms a significant part of the continuum emission from a number of compact sources. Hence, it is surprising that 8.3 GHz and 15 GHz line emission imaged at high resolution is detected from only a handful of sources. A possible reason for this rather low detection rate is lack of sensitivity; we were unable to utilise all of the acquired data in the final analysis. Yet another reason is that the thermal gas detected in continuum images by UA97 is at densities very different from 10^3 - 10^4 cm $^{-3}$ and hence cannot be traced efficiently by its H92 α line emission (see section 6.6.2 for further details). Sub-arcsecond observations of the 1.4 GHz line could possibly detect this gas. Even among the H92 α line sources detected, a fraction do not have recognizable continuum counterparts, which we attribute to confusion with the much stronger compact non-thermal sources.

In section 3.4.3.2, the IR peak was tentatively identified with the line emission from the continuum source 5.59–41.6, since this is the closest to the expected position of the IR peak. However, as was mentioned, detailed astrometry studies indicate that this radio continuum source might not coincident with the position of the IR peak. The primary property of the IR peak is that it dominates the NIR, and especially the MIR emission in NGC 253 and accounts for more than 10 % of the total IRAS flux. It is also the strongest source in infrared emission lines like Br γ and [NeII]. However, it seems to have no readily identifiable conspicuous radio continuum counterpart. The radio continuum emission is known to peak in a region $\sim 3''$ NE of the IR peak, defined as the radio nucleus. This is not surprising since the continuum emission is dominated by non-thermal radiation and the radio nuclear emission is predominantly non-thermal in nature. However, the cm-wave recombination line emissions at 8.3 GHz and 15 GHz (this work) and also the 45 GHz line emission (Zhao et al., 2001) all peak towards and around the radio continuum nucleus as well. The H92 α line intensity towards 5.59–41.6, the nearest source to the IR peak, is comparable to the rest of the line emitting sources. Hence, based on RRL data, there is no reason to expect the IR peak to dominate the IR-observable star formation in NGC 253. Though we are not able to explain this puzzle using available data,

a few possible solutions are outlined in an attempt to reconcile the various multi-wavelength observations of this object. Kalas & Wynn-Williams (1994) predict a free-free flux density of 40 mJy based on the galactic ratio between radio and MIR luminosities. No such continuum source exists near the position of the IR peak (UA97). This led Kalas & Wynn-Williams (1994) to hypothesize a possible dust enshrouded SNR expanding in a molecular cloud which we find implausible. Also, the galactic value for the ratio between radio and MIR emission need not apply in this particular source. Alternatively, the Br γ flux of the IR peak measured by Forbes et al. (1993) implies, for optically thin emission, a free-free flux density of ~ 1 mJy. An extinction of, say, $A_V=10$ even, increases this value to 2.5 mJy. The images of radio continuum emission are consistent with the existence of such a source. Hence the IR peak could be an ordinary star forming site, but with an anomalously high value of MIR excess. On the other hand, the extinction towards the IR peak is much less than that towards the radio nuclear region (Sams et al., 1994) and hence the fact that the IR peak is the most prominent Br γ source and not the radio nucleus can be attributed to dust extinction. The $3.3\ \mu\text{m}$ PAH emission from the IR peak and the radio nucleus are comparable in intensity (Kalas & Wynn-Williams, 1994). The $11\ \mu\text{m}$ PAH emission, however, is much stronger towards the IR peak compared to the nucleus (Keto et al., 1999). The ionization rate in different H 92α emitting regions has been computed from RRL modelling in the previous sections. The total N_{Lyc} in the '15 pc region' is $(2-4)\times 10^{52}\ \text{s}^{-1}$ but is ten times less for 5.59–41.6. Therefore it is surprising that the [NeII] emission, which is proportional to the ionization rate, is stronger towards the IR peak compared to the nuclear region (Böker et al., 1998; Keto et al., 1999). If this difference is attributed to dust extinction, even at the wavelength of [NeII] emission of $12.8\ \mu\text{m}$, then an A_V greater than 100 magnitudes is required towards the nucleus. There is no evidence for such large values of extinction. [NeII] emission is expected to arise from HII regions. NeII is the dominant ionization species of Ne in such regions since the ionization potential of NeI is 22 eV, whereas for NeII, its value is 47 eV. However, if the central '15 pc region' hosts an AGN, then the ultraviolet radiation would be much harder than from stellar clusters and hence it is possible that a substantial fraction of Neon exists in the doubly ionized state, thus leading to weak [NeII] emission. Using the value of N_{Lyc} derived from our RRL models, the [NeII] line integrated flux of the '15 pc region' is calculated to be ~ 6 times more than what is measured by Keto et al. (1999). A PAH feature has been identified at a wavelength of $12.7\ \mu\text{m}$ in the Galactic HII region M 17 (Verstraete et al., 1996) and hence the inconsistencies between the derived ionization and the observed [NeII] line emission at $12.8\ \mu\text{m}$ might be traced back to blending of these two lines. Studies of the [NeII] emission from NGC 253, however, do not mention this possibility. It is therefore still not clear as to why the IR peak is the most prominent feature in IR continuum and line images but is however not readily identifiable through its recombination line emission. Another possible reason is that the density of gas in the IR peak is very different from that derived from H 92α emission. If the density is much lower, say $\lesssim \text{few } 100\ \text{cm}^{-3}$, then a higher resolution image of the 1.4 GHz RRL emission using the A configuration VLA would identify most of the H 166α line as arising from the position of the IR peak. On the other hand, if the gas density is $\gtrsim 10^5\ \text{cm}^{-3}$, then high resolution observations of the mm-wave RRLs would detect this object. It is interesting to note that the second brightest peak of the low resolution H 92α line emission in Anantharamaiah & Goss (1996) is seen close to the IR peak but is not so in our high resolution images. This is evidence that the gas density at the IR peak is much lower than a few 1000

cm^{-3} and hence we predict that the 1.4 GHz line emission, imaged at high resolution, will have a significant maximum towards the IR peak.

The line emission detected towards the radio nucleus was shown to be probably ionized by an AGN. We have identified three other compact H92 α line emitting sources within 9 pc of the radio nucleus and hence the sources of ionization for these three objects also need to be determined. The lines from these sources have large widths, $\sim 200 \text{ km s}^{-1}$, similar to that of the nuclear line emission. We outline plausible scenarios in order to explain these observations.

All four H92 α sources in the ‘15 pc region’ could be HII regions internally ionized by star clusters assumed to be present within them. Based on the ionization rates and sizes derived from RRL modelling, such clusters, if present, would belong to the class of Super Star Clusters (SSCs; Meurer et al. 1995). However, the line widths of the spectra from each of the four sources are $\sim 200 \text{ km s}^{-1}$. Hence, if the line widths are caused by the expansion of the HII regions due to overpressure as well as stellar winds, then the dynamical age for the gas is $\sim 10^4$ years which is too young an age. A star cluster which possesses enough OB stars to provide an ionization in excess of $10^{51} \text{ photons s}^{-1}$ must be at least 10^5 years old. For a Salpeter IMF extending down to $0.1 M_{\odot}$, the escape velocity at a radius of 3 pc is close to 20 km s^{-1} and hence the thermal gas is not gravitationally bound to the clusters. Hence the ionized gas will have to be confined inside the observed volume for a period longer than the dynamical age by some confining mechanism, or, there must be continuous mass loading into the intra-cluster environment from inside the cluster. Therefore, even if such HII regions are assumed to exist, then four, or at least three, such objects would have to be present within this ‘15 pc region’. Since the formation of massive stars inhibits star formation in neighbouring regions, all four clusters would have to be born within a period less than a million years. Since the line widths and gas densities are comparable for all four sources, they can be assumed to be of similar ages. The existence of four massive young star clusters in this 15 pc region is consistent with this region being deficient in molecular gas and in fact lying in between two peaks of CS emission (Peng et al., 1996). However, if at least three of the four H92 α sources are ionized by star clusters, then it is surprising that these clusters are not detected prominently in MIR continuum or PAH emission. Based on the above arguments, we conclude that it is unlikely that the thermal gas in these four line sources are ionized by star clusters within them.

On the other hand, it is now confirmed from X-ray observations by Weaver et al. (2002) that the radio nucleus is powered by a weakly accreting supermassive black hole or an intermediate mass black hole. Assuming the former, the kinematics of the surrounding gas will then be determined primarily by the gravitational potential of the central mass. In this picture, the large width of the H92 α line from the radio nucleus can be attributed to motion of the ionized gas around the centre, thus leading to an estimate of the central mass of few times $10^6 M_{\odot}$. It was argued in section 3.3 that the line emitting gas in the radio nucleus is probably ionized by the UV photons from the AGN. However, even in the presence of the AGN, there are two possible scenarios for the ionization of these sources. The line emitting gas in the nucleus as well as the three other sources could be externally ionized either by the AGN or by star clusters present in this volume. In either case, the line widths of all four sources could be caused by gas motions due to the central mass. This obviates the problem of the short dynamical age of the HII gas. If the primary ionizing source is the AGN, then most of the neon could well be in the doubly ionized state, explaining the dearth of [NeII] emission at $12.8 \mu\text{m}$. An intense hard UV radiation

field would also explain the lack of prominent PAH emission which is expected, given the value of the total N_{Lyc} derived in this volume. On the other hand, the gas could be ionized by star clusters situated external to the line emitting gas, but its motion could be determined by the central mass. The three sources of line emission apart from the nucleus could be, rather than HII regions around star clusters, just density enhancements in the ambient gas. If this were true, then the observed line widths can be attributed to velocity gradients inside an area covered by the resolution element. Then, with sufficiently high spatial resolution, we predict that the width of the radio recombination lines from this region should decrease to values much less than 200 km s^{-1} . It should be noted that RRL observations have detected up to four sources of thermal gas in this region. However, much higher resolution continuum observations (UA97, this work) show the presence of a large number of compact continuum sources less than a few pc in size, believed to be non-thermal emission from supernova remnants. This is, therefore, evidence for active star formation in this '15 pc region', though probably older than the OB stars ionizing the line emitting gas.

What has been discussed above are plausible scenarios for the central 15 pc region of NGC 253. Future higher resolution observations coupled with better astrometry between different wavebands should help decide between these various options. However, the situation outlined above is not without any corroboration; the structure of the central part of the Galaxy is now known and can be compared with. A massive (few times $10^6 M_{\odot}$) low luminosity black hole exists at the centre, coincident with the radio source Sgr A*. A circumnuclear disk (CND) of molecular, and neutral gas and dust surrounds this object, with an inner radius of almost 2 pc. In this region lies the HII region Sgr A West of size $2 \text{ pc} \times 3 \text{ pc}$, density $\sim 10^3 \text{ cm}^{-3}$ and mass of $\sim 250 M_{\odot}$ (Mezger, Duschl & Zylka, 1996). Inside the CND and inner to Sgr A West is the ionized gas feature known as the mini-spiral. The gas density here is as high as 10^4 cm^{-3} though the total gas mass is not more than $10 M_{\odot}$. A number (<100) of young O and WR stars exist within the CND and in fact, a good fraction of these stars with a stellar-wind lie within 0.1 pc of Sgr A* which shows that it is indeed possible for stars to exist close to a central AGN. The thermal gas in the mini-spiral and much of Sgr A West is believed to be ionized by the stars inside the CND. Their dynamics, however, is determined mainly by the potential of the central mass. Earlier low resolution observations of the [NeII] line at $12.8 \mu\text{m}$ showed line widths of $200\text{--}400 \text{ km s}^{-1}$. However, higher resolution imaging showed that the intrinsic widths are $\sim 50 \text{ km s}^{-1}$ and the broad lines are due to large velocity gradients in this region (up to $600 \text{ km s}^{-1} \text{ pc}^{-1}$). Also, high resolution observations of RRLs indicated that the ionized gas is extremely clumpy. Thus the earlier observations of individual sources with large line widths are due to clumpiness of the gas along with large velocity gradients. Therefore most of the features invoked to explain the central 15 pc region of NGC 253 seem to have analogues in the Galactic centre, though at a different scale. The total N_{Lyc} within the central 1 pc region of the Galaxy is $\geq 2 \times 10^{51} \text{ s}^{-1}$ and the total ionized gas mass is a few $100 M_{\odot}$. The much larger values of N_{Lyc} and ionized gas mass in NGC 233 can be expected, however, since this galaxy is a starburst with a star formation rate much higher than in the Galactic centre. Therefore, though the model for the ionization of the central 15 pc region of NGC 253 discussed does not have confirmatory evidence, there exists interesting analogies with the Galactic Centre.

It was shown in section 3.4.3.2 that the four extranuclear sources are ionized by star cluster which are almost in the SSC class. The widths of the RRLs from these sources indicate that the

dynamical ages of these nebulae are $\lesssim 10^5$ years, similar to the derived ages of the supernebulae in NGC 5253, He 2-10 and also the four H92 α line sources in the central 15 pc region of NGC 253. Apart from the interesting fact that the H92 α line seems to be an excellent tracer of compact dense very young nebulae around massive clusters, it is also noteworthy that no such dense compact HII region has been discovered which does not exhibit supersonic line widths. Whether this is a selection effect of the RRL observations or whether supersonic line widths are an intrinsic property of nebulae around SSCs is a question that needs to be answered.

The kinematics of the ionized gas has not been discussed so far. Anantharamaiah & Goss (1996) observed the H92 α line in NGC 253 at lower resolution and derived the velocity field which shows systematic features. Later, Das, Anantharamaiah & Yun (2001) modelled this velocity field in detail, as being caused by a stellar bar and showed that the line emitting ionized gas is consistent with being along the anti-bar x_2 orbits of the bar potential. Such a conclusion was also arrived at by Peng et al. (1996) based on the kinematics of the CS emission. However, much of the RRL emission arises in the central ‘15 pc region’ surrounding the radio nucleus, which is believed to be at the dynamical centre. Therefore, the radio nucleus, and its associated line emission, is expected to lie at the centre of the x_2 orbit and not on it. The locations of the various continuum and line emitting sources in NGC 253 along the line of sight are not known. In the model of Das, Anantharamaiah & Yun (2001), since the x_2 ring is almost edge-on in projection, these sources could be on either side of the ring. If the three other line emitting sources in the central ‘15 pc region’ are not physically associated with the radio nucleus which is at the dynamical centre, but are situated along the surrounding x_2 orbit, then they would necessarily have to be individual star clusters. This uncertainty cannot be resolved easily. The velocity field of the ionized gas in the ‘15 pc region’ indicates that the velocity gradient is almost in the east-west direction and the value increased from 200 to 230 km s $^{-1}$ from east to west, consistent with the observations of Anantharamaiah & Goss (1996).

A three-component model has been derived in section 3.4.3.4 for the ionized gas in NGC 253, similar to that of Arp 220 (Anantharamaiah et al., 2000). Less than half the total 8.3 GHz H92 α line emission measured at lower resolution has been detected in our higher resolution observations. Component I of the ionized gas is responsible for this high intensity part of the H92 α line and produces negligible amounts of line emission at 1.4 GHz. The density of this component is $\sim 10^4$ cm $^{-3}$ and the total ionization requirement is $(3-5.5) \times 10^{52}$ s $^{-1}$, with an ionized gas mass of 5000-10000 M $_{\odot}$. The total area subtended by this component of ionized gas is small, <10 pc. Models of high resolution observations of molecular gas in this galaxy (HCN: Paglione, Tosaki, Jackson 1995; CS: Peng et al. 1996) indicate that the density of the molecular gas exceeds 10^4 cm $^{-3}$. Hence component I of ionized gas can be produced by ionizing the surrounding molecular material. Component II produces almost all of the observed H166 α line at 1.4 GHz and also the remaining H92 α emission not detected at high resolution. This component of ionized gas has a density of ~ 500 cm $^{-3}$, a similar value of $N_{\text{Ly}\alpha}$ of $(4-6) \times 10^{52}$ s $^{-1}$ and a much higher ionized gas mass of $(2-5) \times 10^5$ M $_{\odot}$. The typical transverse size of this component is a few tens of pc. A third component of gas is also needed to explain the observed H40 α emission at 99 GHz, whose density is higher than 10^4 cm $^{-3}$. Hence the multi-frequency RRL data for this galaxy has led to a multi-density model for the ionized gas. This shows the complexity of RRL emission from such a large area; note that the low resolution RRL data at precisely the frequencies we have modelled here, led Puxley et al. (1997) to conclude that all

of these line emissions arise in a single component of gas, which is now shown not to be the case. The entire line emission at 1.4 GHz, 4.8 GHz and 8.3 GHz were modelled as arising in a single component of ionized gas in section 3.4.3.1, constrained by the 99 GHz line emission as an upper limit. Interestingly, the ionization rate derived in this global model is 8×10^{52} , which is close to the sum of the ionization rates of components I and II. However, the derived gas density in the global model is similar to that of component II. It is consistent that a component of low density diffuse gas along with more than one compact high density component of ionized gas has been deduced. The spectral index of the radio continuum emission in NGC 253 is not very steep (UA97, this work). This implies that either free-free emission forms a significant part of the total continuum emission, which is improbable given other ionized gas tracers, or that there is a component of foreground ionized gas with large covering factor absorbing the background non-thermal emission. This ionized gas component must not be optically thin even at 8 GHz. Obviously, component I does not satisfy these requirements but component II indeed does. However, the location of the component II gas is unknown and needs to be investigated. We predict, for example, that there would be significant amount of this gas at the position of the IR peak. Higher resolution observations of the H166 α line using the A array should settle this issue, if combined with lower resolution H92 α emission images. Also, it would be interesting to compare our results with the value of density derived from existing ISO observations of fine structure line (Sturm et al., 2000; Fischer et al., 1999). Modelling the higher density gas which would produce the observed H40 α line emission has not been attempted since the signal-to-noise ratio of the data is not very high. However, sensitive observations of the 45 GHz RRL and also mm-wave RRLs have been carried out using the VLA and IRAM respectively (Zhao, private communications; Viallefond, private communication) and such a modelling can be attempted for this data, in conjunction with the constraints imposed by components I and II. In particular, the 45 GHz and 99 GHz continuum emission of these two components would constrain the continuum emission and hence the properties of the higher density component III.

3.5 Summary and Conclusions

The 1.4 GHz line emission, which is marginally spatially resolved, is detected with a resolution of ~ 50 pc. The 8.3 GHz H92 α and 15 GHz H75 α line emissions have also been imaged, at high resolutions (~ 4 pc and ~ 2 pc respectively). The H92 α emission, which is about half the value measured at low resolution, consists of an extended region of emission surrounding the radio nucleus (the ‘15 pc region’) and four compact sources in the outer disk. The peak of the line emission is towards the radio nucleus. The FWHM of the outer sources is ≤ 100 km s $^{-1}$ whereas the line widths of the sources in the inner 15 pc is about 200 km s $^{-1}$. The line emission in the 15 pc region can be decomposed into four more compact sources. H75 α emission has been detected from only two of these sources, including the radio nucleus. Not all the H92 α line sources have identifiable continuum counterparts.

There exists some evidence for the presence of an AGN at the radio nucleus. We model the density, line width, size, gas mass and ionization of the radio nucleus in terms of three possible ionizing sources. A supernova remnant expanding in a dense medium is ruled out from dynamical considerations. A stellar source implies the existence of a Super Star Cluster. In a stellar wind model, the age of the line emitting HII region is derived to be close to 30000

years. A nebula (and hence a cluster) this young is considered unrealistic and hence a more sophisticated model of a nebula, including stellar wind collisions and mass outflows is required in order to retain a star cluster as the ionizing source. Lastly, a weak AGN is considered. Though the line width and the required ionizing luminosity can indeed be explained, the X-ray flux is too weak and hence a hybrid model has been proposed in order to reconcile the multi-wavelength spectrum with an AGN model. However, recent observations have confirmed the existence of an AGN in the nucleus and have also explained the X-ray deficit by their deduction of a large column density obscuring gas. We do not rule out, however, the possibility of the co-existence of an AGN and a star cluster.

We show that, in contrast to existing interpretations, multi-wavelength RRL emission from NGC 253 does not arise in optically thin gas in LTE. The four extranuclear H92 α sources as well as the four compact sources in the 15 pc region are modelled individually and are seen to arise in gas at densities close to 10^4 cm^{-3} , within a factor of two. The total ionization and gas mass in this high density component are $\sim 4 \times 10^{52} \text{ s}^{-1}$ and 5000-10000 $M_{\odot}$. This component produces a negligible fraction of the 1.4 GHz line emission. A second component of ionized gas with a lesser density of a few 100 cm^{-3} and similar ionization but a gas mass a factor of 10 higher than the higher density component is needed to explain the remainder of the cm-wave RRLs. The observed mm-wave RRL needs yet another component of ionized gas at a density much higher than 10^4 cm^{-3} which has not been modelled in this work.

In conclusion,

- The nature of the radio nucleus is probably an underluminous massive AGN. The additional presence of an SSC is not ruled out.
- The ionized gas component in NGC 253 is decomposed into atleast three distinct components: a low density component ($\sim 500 \text{ cm}^{-3}$) which contributes to most of the observed thermal radio continuum emission and almost all of the 1.4 GHz RRL; a higher density component ($\sim 10^4 \text{ cm}^{-3}$) which is more localised and exhibits supersonic line widths, and a third component at a much higher density.
- Almost all of the H92 α line sources detected at high resolution arise in compact ($< 5 \text{ pc}$) dense ($\sim 10^4 \text{ cm}^{-3}$) nebulae around massive clusters (greater than a few hundred O stars) and also exhibit supersonic line widths.
- The nature of the IR peak is uncertain and probably contains low density gas ionized by a star cluster which is much less obscured than the central 15 pc region.
- The ionization of the line emitting high density thermal gas in the 15 pc region is probably determined by obscured star clusters and the dynamics is determined by the AGN, like the Galactic centre. Alternatively, we might have discovered further examples of supernebulae with large line widths sustained by internal gas dynamical processes.