

## Chapter 4

# NGC 5253 and Henize 2-10 : blue compact dwarf galaxies

### 4.1 Introduction

NGC 5253 and Henize 2-10 form a part of the sample of seven starburst galaxies described in section 2.2.1. These RRL study of these two objects forms the subject of this chapter and the remaining five galaxies are discussed in chapter 6. NGC 5253 and Henize 2-10 are classic examples of BCDGs, or Blue Compact Dwarf Galaxies. BCDGs are dwarf galaxies which are dominated by an ongoing starburst, with or without background quiescent star formation. NGC 5253 ( $D=4.1$  Mpc, Saha et al. 1995) is a dwarf galaxy with an underlying elliptical structure (Caldwell & Phillips, 1989). This galaxy has large scale ionized filaments (Graham, 1981) and a number of young star clusters in the halo (van den Bergh, 1980). The central kpc region is undergoing active star formation and hosts a number of Super Star Clusters (SSCs) (Turner, Beck, & Ho, 2000; Calzetti et al., 1997; Gorjian, 1996; Beck et al., 1996; Meurer et al., 1995; Caldwell & Phillips, 1989). Wolf-Rayet emission has been detected in the central region (Campbell, Terlevich, & Melnick, 1986; Walsh & Roy, 1987, 1989; Schaerer et al., 1997). Based on modelling of the stellar emission and through the presence of ambient ionized gas and Wolf-Rayet features (Gorjian, 1996), a spatial age gradient in the star formation in the core has been inferred. NGC 5253 is notable for having a flat radio continuum spectrum (Lequeux, 1971; Beck et al., 1996), which is attributed to lack of non-thermal radiation due to the absence of supernova remnants. This absence is believed to be due to the very young age of the star formation activity. The resulting age estimate is consistent with that derived from optical and IR spectrophotometry (Beck et al., 1996). The  $H\alpha$  structure in the inner  $20''$  is complex and there is evidence for a patchy dust distribution (Calzetti et al. 1997; hereafter CMB97) . Recently, Turner, Beck, & Ho (2000), hereafter TBH00, have made a high resolution image of the central region in the radio continuum at 15 and 22 GHz and have detected a compact source which they interpret as a ‘supernebula’ surrounding a nascent SSC. This is the first detection of a HII region around a Super Star Cluster.

He 2-10 ( $D=9$  Mpc) was the first Wolf-Rayet galaxy discovered (Allen, Wright & Goss, 1976). Three star forming regions have been identified in the central part of the galaxy and among them, the central  $\sim 5''$  region, called region ‘A’, is the youngest (Méndez et al., 1999). This region exhibits predominant Wolf-Rayet spectral features and is also the most active star forming region. HST imaging in the UV has shown the presence of a linear chain of young

clusters, believed to be SSCs (Conti & Vacca, 1994; Johnson et al., 2000). Deep  $H\alpha$  images of this galaxy (Méndez et al., 1999) indicate a large scale bipolar outflow of gas. Molecular gas, imaged through CO lines, shows a disturbed morphology with a rotating disk or a bar (Kobulnicky et al., 1995). Radio continuum from He 2-10 has an overall spectral index of  $-0.6$  and is therefore dominated by non-thermal emission (Allen, Wright & Goss, 1976). Recent high resolution radio continuum imaging by Kobulnicky & Johnson (1999), hereafter KJ99, has shown the existence of five compact radio knots with flat spectra. These radio knots are interpreted by the authors as high density nebulae surrounding young SSCs, which are probably totally obscured in the optical.

## 4.2 Observations

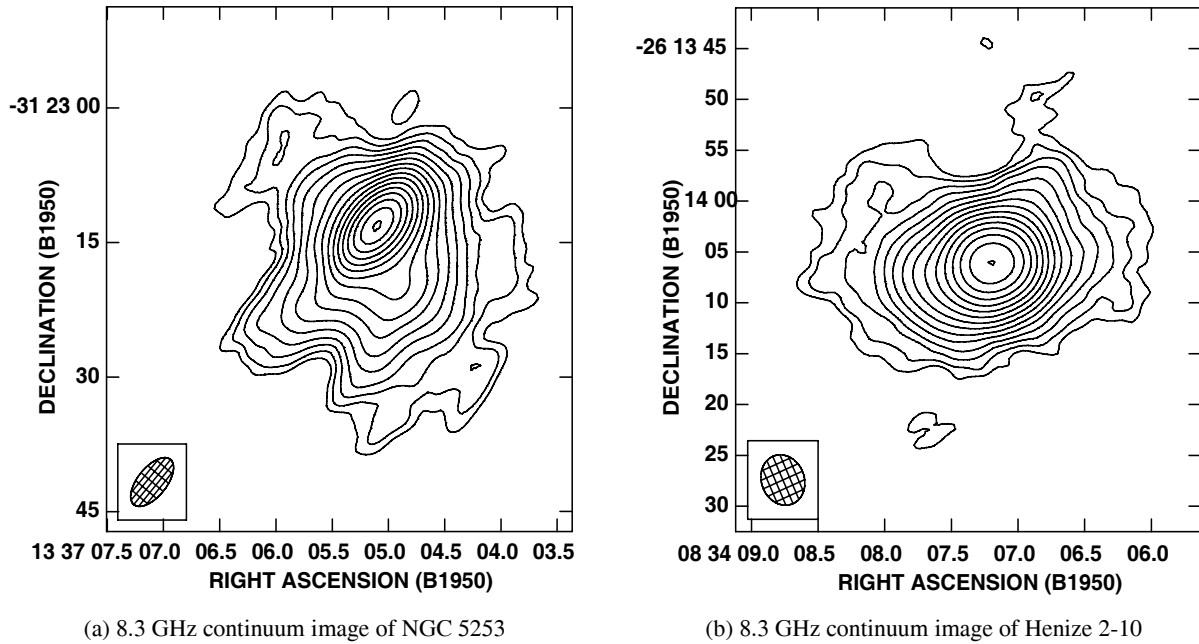


Figure 4.1: 8.3 GHz radio continuum images of (a) NGC 5253 and (b) He 2-10 observed using the combined C and D array VLA data, made with ‘natural weighting’ of the visibilities. The contours start at  $5\sigma$  ( $150\mu\text{Jy}/\text{beam}$  and  $160\mu\text{Jy}/\text{beam}$  for NGC 5253 and He 2-10 respectively) and increase in steps of  $\sqrt{2}$ . The beam sizes are  $6.5'' \times 3.3''$ ,  $\text{PA} = -40^\circ$  for NGC 5253 and  $5.0'' \times 4.3''$ ,  $\text{PA} = 24^\circ$  for He 2-10. For further details, see table 4.1.

NGC 5253 and He 2-10 were observed with the Very Large Array (VLA) in the CnB and the DnC configurations at 8.3 GHz in order to detect the  $H92\alpha$  line. These hybrid configurations were used as the sources are in the southern hemisphere. Some details of the observations are given in table 4.1. The effective velocity resolution is  $113 \text{ km s}^{-1}$ . The CnB and DnC array data of each galaxy were concatenated and the combined continuum and line datasets (with a resolution of  $\sim 5''$ ) were obtained. The continuum and line parameters are presented in table 4.1. Figure 4.1 shows the continuum images of the two galaxies.

The continuum images show evidence for filaments, especially in the case of NGC 5253, where there are extensions in the southern direction. These filaments are also seen in optical line and continuum images and extend out to a few arcminutes. The total continuum flux density

of NGC 5253 at 8.3 GHz is 58 mJy. The radio spectrum of this galaxy is known to be flat from 1.4 GHz up to 23 GHz, based on both single-dish and scaled array VLA observations (see Lequeux 1971 and also Turner, Ho & Beck 1998 and references therein). Lower resolution images indicate that there is emission over at least  $2'$ . The shortest spacing available in the D configuration of the VLA implies that our images are not sensitive to structures on scales larger than  $\sim 2'$ . We estimate that the total flux density of NGC 5253 in our image is 80% of the single-dish flux density at 8.3 GHz. The radio continuum emission in NGC 5253 peaks around region 'A' (the cm-emission peak in Turner, Ho and Beck 1998) which contains the two main star forming regions - clusters 4 and 5 (CMB97). The radio continuum emission is weak to the south of the peak, where the older clusters are believed to have dispersed the surrounding gas. The radio emission in He 2-10 covers the two main star forming regions - 'A' and 'B' (region 'A' is the central  $6''$  region and region 'B' is the secondary star forming region  $8.5''$  east of 'A', Corbin, Korista & Vacca 1993). Figure 4.2 shows the  $H92\alpha$  line spectra of the two galaxies at the position of the peak continuum emission. The line emission in both the galaxies is spatially unresolved, even in the higher resolution C array data.

**Table 4.1: Observational parameters**

|                                                              | NGC 5253             | He 2-10              |
|--------------------------------------------------------------|----------------------|----------------------|
| Phase & bandpass cal.                                        | 1334–127             | 0919–260             |
| $uv$ -range : DnC                                            | 0.7–42               | 0.7–46               |
| CnB                                                          | 1.3–150              | 2.0–130              |
| Date of observation : DnC                                    | 1999 Feb 19          | 1999 Feb 19          |
| CnB                                                          | 1998 Nov 10          | 1998 Nov 10          |
| Synthesized Beam                                             | $6.5'' \times 3.3''$ | $5.0'' \times 4.3''$ |
| P.A. of beam                                                 | $-40^\circ$          | $24^\circ$           |
| Peak 8.3 GHz continuum flux density <sup>a</sup> (mJy/beam)  | 28                   | 13                   |
| Total 8.3 GHz continuum flux density (mJy)                   | 58                   | 29                   |
| Noise in continuum image ( $1\sigma$ ; $\mu$ Jy/beam)        | 27                   | 21                   |
| Peak $H92\alpha$ flux density <sup>a</sup> (mJy/beam)        | 0.53                 | 0.16                 |
| Noise in channel image <sup>b</sup> ( $1\sigma$ ; mJy/beam)  | 0.065                | 0.045                |
| FWHM of $H92\alpha$ <sup>c</sup> ( $\text{km s}^{-1}$ )      | $95 \pm 10$          | $112 \pm 20$         |
| $H92\alpha$ line flux ( $\times 10^{-23} \text{ W m}^{-2}$ ) | $2.8 \pm 0.5$        | $1.0 \pm 0.2$        |
| 4.8 GHz continuum flux density (mJy/beam) <sup>a</sup>       | $30^d$               | $18^e$               |
| 15 GHz continuum flux density (mJy/beam) <sup>a</sup>        | $26^d$               | $9^e$                |

<sup>a</sup>Corresponding to the central  $\sim 5''$  region.

<sup>b</sup>After hanning smoothing.

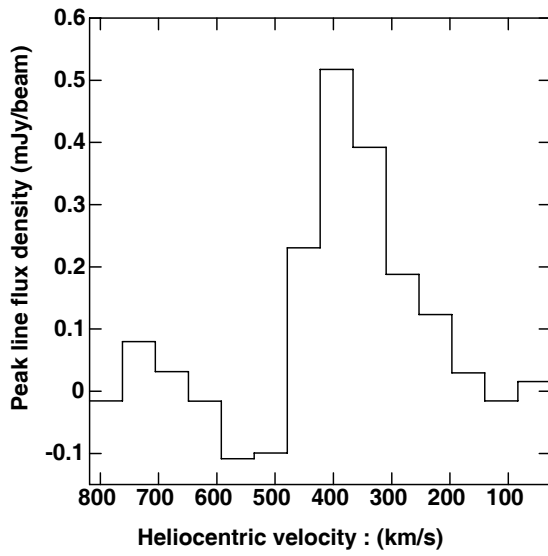
<sup>c</sup>Before hanning smoothing.

<sup>d</sup>From Turner et al. 1998

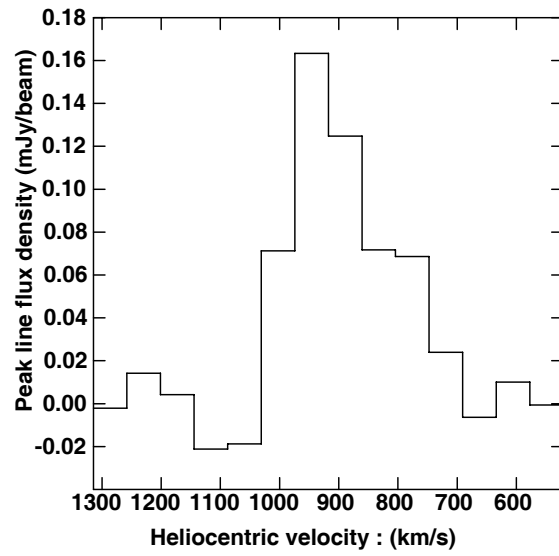
<sup>e</sup>Assuming  $S_\nu \propto \nu^{-0.6}$ ; see Koblunicky and Johnson 1999).

### 4.3 Modelling the ionized gas properties

The models for the RRL emission have been described in section 2.3, where Models I, II, III and IV are for a single spherical HII region, a rectangular slab, a collection of HII regions and a multi-density extension of a collection of HII regions respectively. The observed data were modeled and valid solutions were identified as those combinations of free parameters which



(a) H92 $\alpha$  spectrum towards NGC 5253



(b) H92 $\alpha$  spectrum towards Henize 2-10

Figure 4.2: The hanning smoothed H92 $\alpha$  spectra at the continuum peaks of (a) NGC 5253 and (b) He 2-10 at 8.3 GHz for the combined C and D array VLA data. The line emission is unresolved in both galaxies. The spatial resolution is  $6.5'' \times 3.3''$  for NGC 5253 and  $5.0'' \times 4.3''$  for He 2-10. The velocity resolution of the spectrum is  $113 \text{ km s}^{-1}$ .

produce both the observed H92 $\alpha$  line as well as free-free emission at 4.8, 8.3 and 15 GHz less than the corresponding total observed continuum flux densities (which would include both thermal and non-thermal components). All solutions were computed for  $T_e = 10000$  and  $12500$  K. These high temperatures have been derived from optical spectroscopy and are consistent with the low metallicity of these two galaxies (Campbell, Terlevich, & Melnick, 1986; Walsh & Roy, 1989; Kobulnicky et al., 1997). Model results for the two galaxies are summarised in table 4.2. Since Models I and II give similar results, they are grouped together. The allowed range of values for the densities and sizes of ionized gas are quite limited. The gas properties for the models with the minimum allowed value of  $N_{\text{Lyc}}$  are given in the lower half of table 4.2.

There are two classes of models allowed by the existing data :  $n_e < 2500 \text{ cm}^{-3}$ ,  $l \sim 5 \text{ pc}$  and  $n_e > 2500 \text{ cm}^{-3}$  and  $l \sim 30 \text{ pc}$ . The model solutions are indicated in separate rows for each class of solutions. In the case of Model IV, it can be seen that solutions exist only for values of  $n_e^{\text{min}}$  ranging between  $2500$  and  $25000 \text{ cm}^{-3}$ . Also, the solutions with the minimum values of  $N_{\text{Lyc}}$  (the minimum value of  $N_{\text{Lyc}}$  which is consistent with the given data) correspond to densities between  $5000$  and  $10000 \text{ cm}^{-3}$ . Though no upper limit to the density is imposed on the models, the nature of the allowed solutions is such that only gas of densities very close to  $n_e^{\text{min}}$  contributes to the line flux density and also absorbs almost all of the required ionizing UV photons, i.e., all the higher density gas in the distribution contributes negligible amounts of RRL emission; this result is common to all valid solutions in this model. We find that the allowed combinations of the free parameters  $\alpha$  and  $l_{\text{min}}$  (the latter being derived from  $n_e^{\text{min}}$  and  $c_1$ ; see section 2.3.2) are such that the value of  $n_e^{\text{min}}$  is about  $10^4 \text{ cm}^{-3}$  and the size of the gas at this density (which is the dominant contributor to the total line strength) is between  $3$ - $10 \text{ pc}$ . This result explains why the results of models I, II and III agree well with those of model IV and validates the single-density approximation, as described in section 2.3.2. That both the constant density models as

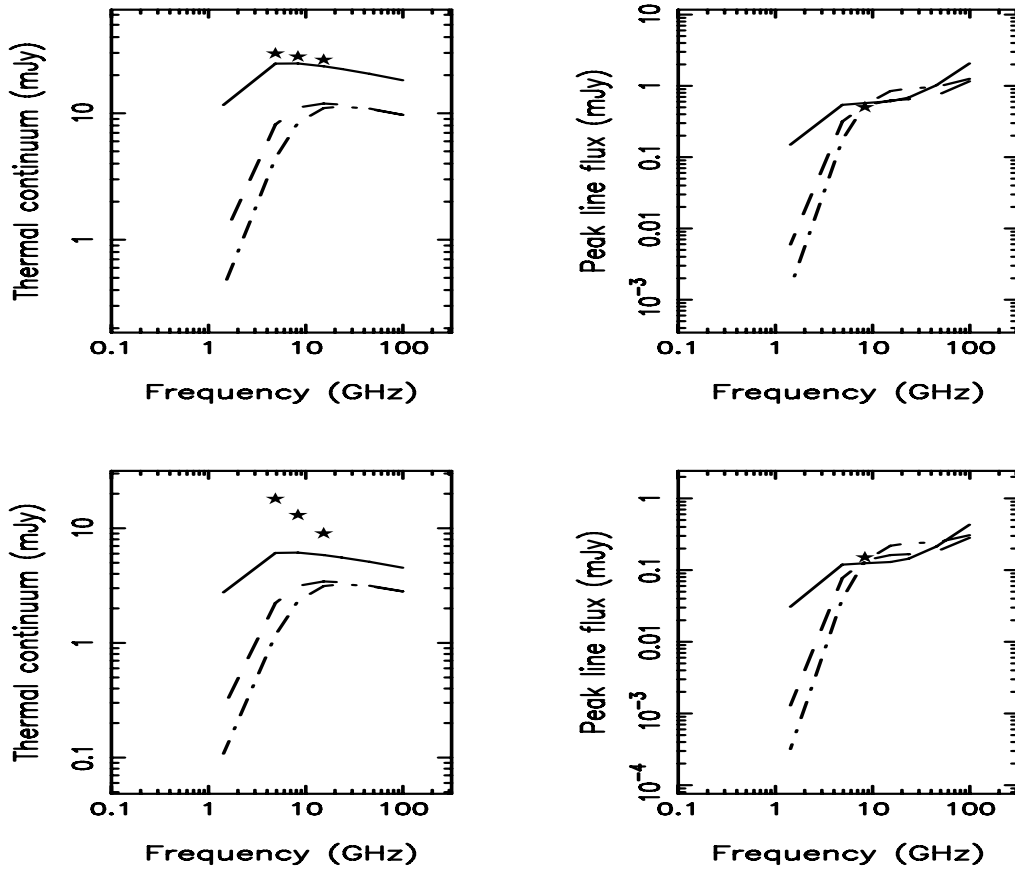


Figure 4.3: Predictions for the thermal continuum and the peak RRL flux densities as a function of frequency, for NGC 5253 (*top*) and He 2-10 (*bottom*) for a few valid solutions corresponding to Model I (single density spherical HII region model). The data points are marked as stars. The solid line corresponds to  $n_e=10^3 \text{ cm}^{-3}$ ,  $l=24 \text{ pc}$ ,  $T_e=10000 \text{ K}$ , the dashed line to  $n_e=5000 \text{ cm}^{-3}$ ,  $l=6 \text{ pc}$ ,  $T_e=10000 \text{ K}$  and the dot-dashed line to  $n_e=10^4 \text{ cm}^{-3}$ ,  $l=4 \text{ pc}$ ,  $T_e=10000 \text{ K}$ . The predictions of Models II-IV are similar.

well as the multiple density models give the same density of  $\sim 10^4 \text{ cm}^{-3}$  is reason enough to believe that most of the ionized gas in this region does indeed have a density close to  $10^4 \text{ cm}^{-3}$ . The predictions of some of the valid model solutions for the free-free continuum and line flux densities as a function of frequency are shown in Figure 4.3. The calculated values of the free-free continuum flux densities are less than the observed total continuum flux densities (which are marked as stars in the figure). The remaining continuum emission which is unaccounted for in our models will have contributions both from thermal continuum from any non-RRL emitting gas and also from the non-thermal continuum (the latter, only in the case of He 2-10, since NGC 5253 has very little contribution from non-thermal emission in the central region). If a significant amount of such a non-RRL emitting thermal gas is present, the amount of such gas will be constrained by the continuum flux densities at  $\nu < 1 \text{ GHz}$ . All the above models will be referred to as ‘low-resolution’ models since these models are based on data with a resolution of  $5''$ , corresponding to a linear size of  $150 \text{ pc}$  for NGC 5253 and  $315 \text{ pc}$  for He 2-10. In all four models, the favored parameters are densities of  $n_e \sim 10^4 \text{ cm}^{-3}$ , effective sizes of  $3\text{-}8 \text{ pc}$  and masses of ionized gas of  $\sim 10^4 M_\odot$ .

Table 4.2 show that for both the galaxies, the four models give results which are consistent. But the minimum value of  $N_{\text{Lyc}}$  varies slightly among the various models. This variation is due to the different geometries assumed in the models and illustrates the uncertainties associated with modelling data with a limited angular resolution.

## 4.4 Super-star Clusters

We now need to explain the derived ionization of a few times  $10^{52} \text{ s}^{-1}$  in both the galaxies. One of the possible models for an ionizing source is a star cluster. As mentioned in section 4.1, TBH00 and KJ99 have detected radio continuum emission from the central parts of the two galaxies, which they attribute to free-free emission. Therefore they conclude that the central region hosts a massive star cluster. Since there is no a priori evidence for the presence of an AGN in either of the galaxies, we assume that the ionizing source responsible for the observed RRLs is also a star cluster. In sections 4.4.1 and 4.4.2, we derive the ionization properties of the star cluster based solely on our low resolutions RRL data. In sections 4.4.3 and 4.4.4, we also consider the radio continuum observations of TBH00 and KJ99 in order to further constrain the properties of the ionizing sources in these objects.

### 4.4.1 Results from the low-resolution RRL data : NGC 5253

Most of the models discussed in the previous section yield electron densities in excess of a few  $1000 \text{ cm}^{-3}$  within an effective size of 2-10 pc (table 4.2). The minimum value of the derived  $N_{\text{Lyc}}$  is  $2.5 \times 10^{52} \text{ s}^{-1}$ . This value of  $N_{\text{Lyc}}$  is computed from the low-resolution data and is consistent with the ionizing photon flux computed from other nebular diagnostics listed below. The continuum flux density of 28 mJy measured from the line emitting region (which is the position of the peak continuum emission, corresponding to the  $6.5'' \times 3.3''$  sized resolution element) in the 8.3 GHz continuum image (table 4.2) corresponds to  $N_{\text{Lyc}} = 3 \times 10^{52} \text{ s}^{-1}$ , based on the assumption of an optically thin gas. The  $\text{Br}\gamma$  flux from the central  $5''$  region (Davies, Sugai, & Ward, 1998) implies an  $N_{\text{Lyc}}$  of  $1.5 \times 10^{52} \text{ s}^{-1}$ . The  $\text{H}\alpha$  flux density inside an aperture of  $5''$  (measured using the  $\text{H}\alpha$  image of CMB97) gives an  $N_{\text{Lyc}}$  of  $1.0 \times 10^{52} \text{ s}^{-1}$ .

Based on the average derived value of  $N_{\text{Lyc}} = 2.5 \times 10^{52} \text{ s}^{-1}$  and using a Salpeter IMF with  $m_{\text{upper}} = 80 M_{\odot}$  and the tables given in Vacca, Garmany, & Shull (1996), the number of O stars (O3-O9) is estimated to be  $\sim 1800$ . It should be noted that we have used the numbers from Vacca, Garmany, & Shull (1996) for solar metallicity whereas the two galaxies NGC 5253 and He 2-10 have sub-solar metallicities; therefore the calculated values of  $N_{\text{Lyc}}$  will be underestimated. However, this error is less than 20% (Vacca, 1994). Assuming  $m_{\text{lower}}$  to be  $1.0 M_{\odot}$ , the total number of stars within a region of size  $\sim 5 \text{ pc}$  is  $\sim 3.5 \times 10^5$ . This  $\sim 5 \text{ pc}$  sized region of gas could be spread over an entire resolution element (150 pc for NGC 5253). On the other hand, if the gas is physically in a compact region of size  $\sim 5 \text{ pc}$ , then the corresponding stellar density indicates that the ionizing source would then be a Super Star Cluster (SSC) (Meurer et al., 1995).

### 4.4.2 Results from the low-resolution RRL data : He 2-10

Similar to the results for NGC 5253, most models for He 2-10 yield electron densities in excess of a few  $1000 \text{ cm}^{-3}$  within an effective size of 2 to 10 pc (table 4.2). The minimum derived

**Table 4.2: The low-resolution model results for NGC 5253 and Henize 2-10**

| Parameter                                          | Models I&II                            |                                         | Model III                        |                                      | Model IV             |                        |
|----------------------------------------------------|----------------------------------------|-----------------------------------------|----------------------------------|--------------------------------------|----------------------|------------------------|
|                                                    | NGC 5253                               | He 2-10                                 | NGC 5253                         | He 2-10                              | NGC 5253             | He 2-10                |
| $n_e$ (cm <sup>-3</sup> ) <sup>a</sup>             | 500-1000<br>5000-10 <sup>4</sup>       | 500-1000<br>5000-10 <sup>4</sup>        | 5000-10 <sup>4</sup>             | 5000-50000                           | 2500-25000           | 2500-25000             |
| Size (pc) <sup>a,b</sup>                           | 20-30<br>2-7                           | 30-40<br>3-8                            | 5-10                             | 2-10                                 | 3-7                  | 2-10                   |
| EM (pc cm <sup>-6</sup> ) <sup>a</sup>             | 2×10 <sup>7</sup><br>2×10 <sup>8</sup> | 2×10 <sup>7</sup><br>≥5×10 <sup>8</sup> | 10 <sup>7</sup> -10 <sup>8</sup> | 5×10 <sup>7</sup> -2×10 <sup>9</sup> | ~10 <sup>8</sup>     | ~10 <sup>8</sup>       |
| M <sub>HII</sub> (M <sub>⊙</sub> )                 | 10 <sup>5</sup><br>10 <sup>4</sup>     | 3×10 <sup>5</sup><br>~10 <sup>4</sup>   | 10 <sup>4</sup>                  | 7000-40000                           | 10 <sup>4</sup>      | 10 <sup>4</sup>        |
| Solutions for minimum N <sub>Lyc</sub>             |                                        |                                         |                                  |                                      |                      |                        |
| N <sub>Lyc</sub> <sup>min</sup> (s <sup>-1</sup> ) | 1.5×10 <sup>52</sup>                   | 2.5×10 <sup>52</sup>                    | 2.5×10 <sup>52</sup>             | 4×10 <sup>52</sup>                   | 3.5×10 <sup>52</sup> | 5×10 <sup>52</sup>     |
| $n_e$ (cm <sup>-3</sup> )                          | 5000-10 <sup>4</sup>                   | 5000-10 <sup>4</sup>                    | 5000-10 <sup>4</sup>             | 5000-50000                           | 5000-10 <sup>4</sup> | 5000-10 <sup>4</sup>   |
| Size (pc) <sup>b</sup>                             | 2-7                                    | 4-7                                     | 4-7                              | 5-10                                 | 3-7                  | 3-7                    |
| EM (pc cm <sup>-6</sup> )                          | 2×10 <sup>8</sup>                      | ≥5×10 <sup>8</sup>                      | ~10 <sup>8</sup>                 | ~10 <sup>8</sup>                     | ~10 <sup>8</sup>     | 3×10 <sup>8</sup>      |
| S <sub>ff</sub> /S <sub>obs</sub> <sup>cont</sup>  | 0.3-0.5                                | 0.2-0.5                                 | ~0.7                             | 0.3-0.7                              | 0.3-0.5              | 0.3-0.6                |
| M <sub>HII</sub> (M <sub>⊙</sub> )                 | 10 <sup>4</sup>                        | ~10 <sup>4</sup>                        | 10 <sup>4</sup>                  | 2×10 <sup>4</sup>                    | 5000-10 <sup>4</sup> | 10 <sup>4</sup> -50000 |
| No. of O stars <sup>c</sup>                        | 1100                                   | 1825                                    | 1825                             | 2900                                 | 2600                 | 3650                   |
| Stellar mass (M <sub>⊙</sub> ) <sup>d</sup>        | 2×10 <sup>5</sup>                      | 3.5×10 <sup>5</sup>                     | 3.5×10 <sup>5</sup>              | 5.5×10 <sup>5</sup>                  | 5×10 <sup>5</sup>    | 7×10 <sup>5</sup>      |

<sup>a</sup>The two rows correspond to two classes of models, both of which are consistent with existing observations. The models predict different RRL and continuum flux densities at other frequencies (see Figure 4.3).

<sup>b</sup> 'Effective' sizes are quoted for Models III and IV, i.e., N<sub>HII</sub><sup>1/3</sup>×*l*, where there are N<sub>HII</sub> HII regions of size *l*.

<sup>c</sup> O3-O9.

<sup>d</sup> Assuming a Salpeter IMF, m<sub>upper</sub>=80 M<sub>⊙</sub> and m<sub>lower</sub>=1.0 M<sub>⊙</sub>.

value of  $N_{\text{Lyc}}$  for the 5'' sized RRL emitting region is  $4 \times 10^{52} \text{ s}^{-1}$ . The central 2'' region has been resolved into a number of star-forming knots and the value of  $N_{\text{Lyc}}$  derived from observations which resolve these knots is comparable to that derived here. Johnson et al. (2000) obtain a value of  $N_{\text{Lyc}} = 2.5 \times 10^{52} \text{ s}^{-1}$  from their UV continuum images, while Doyon, Puxley, & Joseph (1992) derive a value of  $4 \times 10^{52} \text{ s}^{-1}$  from their measured  $\text{Br}\gamma$  flux inside a 5'' aperture. For an  $N_{\text{Lyc}}$  of  $4 \times 10^{52} \text{ s}^{-1}$ , the number of O stars required is  $\sim 2900$  and the total stellar mass is  $\sim 5.5 \times 10^5 M_{\odot}$  (using a Salpeter IMF with  $m_{\text{upper}} = 80 M_{\odot}$  and  $m_{\text{lower}}$  to be  $1.0 M_{\odot}$ , and the results of Vacca, Garmany, & Shull 1996). As in the case of NGC 5253, the corresponding stellar density for a 3-10 pc region corresponds to an SSC, if we assume that the ionized gas is physically confined to this  $\sim 5$  pc region.

Though the derived ionizing photon flux and the length-scale of the gas for both galaxies imply an SSC, the 8.3 GHz RRL data alone does not clarify whether the ionized gas is in a single clump of diameter  $\sim 5$  pc or it is spread out in some unknown geometry over the entire 5'' region. In the latter case, the ionizing source need not be an SSC. In the next section, we present arguments that the ionized gas is indeed much less than 5'' in size. We also discuss the implications of combining our RRL data and model results with recently published sub-arcsecond resolution continuum images of the centres of the two galaxies (obtained by TBH00 for NGC 5253 and by KJ99 for He 2-10).

#### 4.4.3 Compactness of the RRL emission : NGC 5253

We can indirectly infer that the RRL emitting region is smaller than 5'' from the  $\text{H}\alpha$  and  $\text{H}\beta$  images of CMB97. The  $\text{H}\alpha$  image in the inner 5'' is quite clumpy with extensive filaments and knots. Though the RRL emission need not follow the  $\text{H}\alpha$  emission, it is unlikely that the high density gas responsible for RRL emission is spread smoothly over the 150 pc region, given the patchy appearance of the  $\text{H}\alpha$  emission. and hence we may conclude that the RRL emitting gas must also be patchy within the 5'' beam.

TBH00 have imaged NGC 5253 at 23 GHz and 15 GHz with the VLA with angular resolutions of 0.13'' and 0.2'', respectively. A compact ( $\sim 0.1''$ , or 2 pc) source with a flux density of 11 mJy at 15 GHz, and hence a brightness temperature of  $12000 \pm 3000 \text{ K}$ , was discovered. This was interpreted as a HII region, and in addition, these authors detect radio emission at a low level with a size of 1-2''. Further confirmation of the thermal nature of this source comes from recently detected IR emission from the central object at 11.7 and  $18.7 \mu\text{m}$  (Gorjian, Turner, & Beck, 2001). Though the RRL emission is not expected to exactly follow the morphology of continuum emission (since a particular RRL comes from a limited range of densities, and the continuum emission is sensitive to all densities if optically thin), no line emission is expected from continuum-free regions and hence we can associate the observed  $\text{H}92\alpha$  emission with the inner 1-2'' region. Assuming that the observed radio continuum emission from this galaxy is purely due to free-free emission, TBH00 derive an rms electron density of  $4 \times 10^4 \text{ cm}^{-3}$  and an  $N_{\text{Lyc}}$  of  $4 \times 10^{52} \text{ s}^{-1}$ . From the ionization requirement and the size of the object, TBH00 suggest that this compact source is a 'supernebula' surrounding an SSC. Since this source is the strongest radio continuum source in the inner 5'' region and since the derived properties of the 'supernebula', especially the local electron density, match those derived from the RRL data, we identify the RRL emitting gas with the continuum source detected by TBH00. Therefore, we have modeled the 'supernebula' to estimate the fraction of the observed RRL emission this

compact source is capable of producing. The models are constructed to produce the observed 11 mJy continuum emission at 15 GHz from gas of size  $\leq 0.1''$ . In addition, the continuum and RRL emission by this gas at 8.3 GHz is also constrained to be less than the observed values (the latter two constraints are imposed as upper limits since the observed values correspond to the larger  $5''$  area). The results of this model are summarised in Table 4.3. Only 10-35% of the observed 8.3 GHz line emission can be explained by the TBH00 ‘supernebula’. All densities  $\geq 5 \times 10^4 \text{ cm}^{-3}$  are consistent with the existing observations. The remaining line emission presumably originates in the surrounding larger nebulosity with a size of  $1-2''$ . A calculation similar to the one above, where we model the inner  $3''$  region with a 15 GHz flux density of 22 mJy (TBH00), shows that such a model is indeed capable of explaining the entire observed RRL line emission.

The ‘supernebula’, as imaged by TBH00 is separated by about  $0.9''$  from the position of the brightest  $\text{H}\alpha$  knot in CMB97. This knot was identified with the UV Cluster 5 in the HST image by Meurer et al. (1995). Since the  $1\sigma$  error between the absolute reference frames of the Guide Star Catalogue 1 of the HST, on which the  $\text{H}\alpha$  and UV images are based, and the extragalactic radio reference frame, on which the images in TBH00 are based, is  $0.5''$  (Russell et al., 1990 and also Calzetti, and Rajagopal, private communication), the radio ‘supernebula’ of TBH00 can also be identified with the  $\text{H}\alpha$  peak (and hence the UV cluster 5) within these errors. The significance of this identification is two-fold. (1) An additional highly obscured SSC need not be invoked and (2) we can relate the known properties of the optical cluster with those of the ‘supernebula’. The  $\text{H}\alpha$  flux for this cluster is  $4.8 \times 10^{-16} \text{ W m}^{-2}$  (see CMB97) from which we infer the value of  $N_{\text{Lyc}}$  to be  $\sim 1.3 \times 10^{51} \text{ s}^{-1}$ . The discrepancy between this value and  $N_{\text{Lyc}} > 2.5 \times 10^{52} \text{ s}^{-1}$  which is derived from radio continuum data (Table 3) can be attributed to extinction. However, as the age of the optical cluster is well constrained, the dynamical age of the ionized ‘supernebula’ around it needs to be consistent with this cluster age and this is discussed in section 4.5.

**Table 4.3: Model results for 8.3 GHz line and the high resolution continuum data of KJ99 and TBH00**

| Parameter                                                                   | NGC 5253                                | He 2-10                |
|-----------------------------------------------------------------------------|-----------------------------------------|------------------------|
| $n_e \text{ (cm}^{-3}\text{)}$                                              | $5 \times 10^4 - 10^6$                  | 5000-10000             |
| Size (pc)                                                                   | 1.0-2                                   | $\sim 7$               |
| $N_{\text{Lyc}} \text{ (s}^{-1}\text{)}$                                    | $> (2.5-4.0) \times 10^{52} \text{ }^a$ | $> 2.5 \times 10^{52}$ |
| $\tau_c$                                                                    | $\geq 10$                               | $\sim 0.6$             |
| $[S_{\text{H}92\alpha}]_{\text{model}}/[S_{\text{H}92\alpha}]_{\text{obs}}$ | 0.1-0.35                                | $\sim 1$               |
| $M_{\text{HII}} \text{ (M}_{\odot}\text{)}$                                 | $\geq 2000$                             | $\geq 2 \times 10^4$   |
| No. of O stars <sup>b</sup>                                                 | >1900-2900                              | >1900                  |
| Mass of stars $\text{(M}_{\odot}\text{)}^c$                                 | $> (3.5-5.5) \times 10^5$               | $> 3.5 \times 10^5$    |

<sup>a</sup>The range 2.5-4 is over various models.

<sup>b</sup>O3-O9.

<sup>c</sup>Assuming a Salpeter IMF with  $m_{\text{upper}}=80 \text{ M}_{\odot}$  and  $m_{\text{lower}}=1.0 \text{ M}_{\odot}$ .

#### 4.4.4 Compactness of the RRL emission : He 2-10

The central  $5''$  region harbors about nine UV clusters, possibly SSCs, arranged in an arc of size  $\sim 2''$  (Conti & Vacca, 1994). This region contains clumpy ionized gas and also large dust

extinction which is patchy. The  $\text{Br}\gamma$ , UV and optical continuum images of the centre show the presence of several knots (Davies, Sugai, & Ward, 1998; Conti & Vacca, 1994; Johnson et al., 2000). KJ99 have imaged the radio continuum emission of the nucleus of Henize 2-10 with an angular resolution of  $0.5''$  using the VLA. They detect 4-5 compact knots, each of diameter  $\sim 0.6''$ , arranged within a  $5'' \times 2''$  region. These various knots of star formation detected individually in the optical,  $\text{H}\alpha$ ,  $\text{Br}\gamma$  and radio continuum are not positionally consistent, possibly due to intrinsic astrometric errors. Attempts at aligning the various images using global astrometric offset corrections have shown that not all knots have counterparts at all wavelengths (KJ99 and Johnson et al. 2000); thus there appears to be hidden regions of star formation in the central  $5''$  region. This morphological evidence for the presence of clumpy gas at the centre indicates that the RRL emitting gas is also clumpy on scales  $< 5''$ .

Based on the continuum spectra, KJ99 infer that the radio knots consist of thermal gas at densities  $1500\text{--}5000\text{ cm}^{-3}$  (optically thick at 8.3 GHz) and also derive a total  $N_{\text{Ly}\alpha}$  of  $4 \times 10^{52}\text{ s}^{-1}$ . They suggest that each compact knot may be ionized by a SSC. We have modeled this region to look for solutions which produce the observed radio continuum flux densities at 15, 8 and 5 GHz, as reported by KJ99. The allowed solutions are also constrained to produce either all or a part of the observed  $\text{H}2\alpha$  line. The model results are listed in Table 4.3 and these radio knots, if thermal, are indeed capable of producing all of the observed  $\text{H}2\alpha$  recombination line. Therefore we identify these multiple radio continuum knots with the gas responsible for emitting the observed RRL at 8.3 GHz and associate the ionizing sources with SSCs.

## 4.5 Properties of the ‘supernebulae’

The detection of a RRL from the central region of both galaxies with parameters similar to those derived by TBH00 and KJ99 is added confirmation for the thermal nature of the central compact source(s). The values of the local electron densities of the ‘supernebulae’ derived from the RRL data agree very well with the rms densities derived from the radio continuum data. Therefore we conclude that the filling factor of the ionized gas inside the  $\sim 5\text{ pc}$  region in both the galaxies is near unity. That is, each of the observed ‘supernebulae’ are probably single Stromgren spheres around a cluster rather than a collection of compact HII regions and hence Model I is the most appropriate geometry to use for these two galaxies.

A question not yet addressed regards the dynamics and time-scales involved in explaining the existence of  $\sim 10^4\text{ M}_{\odot}$  of ionized gas within a few parsecs of an SSC. In this section, we will identify the ‘supernebula(e)’ with the RRL emitting gas in both the galaxies. The observed FWHM of  $\sim 100\text{ km s}^{-1}$  (estimated from the spectrum after correcting for effects of offline hanning smoothing as well as finite spectral resolution) within a 2-8 pc sized region implies a dynamical expansion time of  $(2\text{--}8) \times 10^4$  years, quite short compared to the estimated age of  $(1\text{--}3) \times 10^6$  years for the central cluster in NGC 5253. Therefore, either the supernebula must have been set into motion extremely recently, or there must exist some confining mechanism operating in the central region. In addition, strong stellar winds from OB and Wolf-Rayet stars as well as the natural expansion of the HII region due to overpressure would drive the ionized gas outwards. Given the large mass, high density and small size of the observed HII region ( $\sim 2\text{ pc}$  for the ‘supernebula’ of TBH00 and KJ99 and 5-8 pc for the RRL emitting gas), dynamical models should constrain both the age of the SSC as well as the density of the ambient unshocked

medium. For NGC 5253, for example, if the ‘supernebula’ is identified with the UV Cluster 5, then the age is determined to be less than 3 million years (CMB97) but not less than about a million years. Hence this problem of too small a dynamical age is reminiscent of the situation for the radio nucleus in NGC 253 (see section 4.3). However, there are a few differences. First, there is, to date, no evidence at all for the possible existence of an AGN in the centre of NGC 5253. Second, both NGC 5253 and He 2-10 are well-known WR galaxies and hence WR stars with their associated strong stellar winds can be expected to be present in almost all star clusters in these galaxies. Specifically, if the supernebula in NGC 5253 is associated with the UV Cluster 5, it should be noted that WR features have indeed been detected from this cluster. Hence, the effect of stellar winds will have to be taken into account.

We model the observed properties of the supernebula using the stellar-wind driven model. This model has been described in detail in section 3.3.2.2 in the context of the line emission from the radio nucleus of NGC 253. The free parameters are the age of the nebula, the ambient density of the interstellar medium and the star formation rate. The time dependent ionizing photon rate and the mechanical luminosity of the stellar winds are obtained from the Starburst 99 code (Leitherer et al., 1999). In this model, a shock front advances into the ambient medium, powered by mainly by the stellar winds from the massive stars in the central cluster. The matter swept-up by this shock cools and forms a thin dense shell which is assumed to trap all of the ionizing photons emanating from within. The expansion velocity of this shell, which is the source of the observed RRL emission, is assumed to have a value half that of the observed FWHM of the RRL, namely,  $50 \text{ km s}^{-1}$ . Based on the derived ionization rate for NGC 5253, the total stellar mass for a Salpeter IMF is  $\sim 3 \times 10^5 M_{\odot}$  for a lower mass cutoff of  $1 M_{\odot}$  and  $\sim 8 \times 10^5 M_{\odot}$  for a lower mass cutoff of  $0.1 M_{\odot}$ . Hence, for a radius greater than  $\sim 3 \text{ pc}$ , the escape velocity from this cluster is less than the assumed expansion velocity of  $50 \text{ km s}^{-1}$  and the effect of gravity can be neglected in this analysis. Since the masses of each of the star clusters in He 2-10 are less than that of NGC 5253, gravity can be neglected in the case of the supernebulae in He 2-10 as well. The constraints imposed on the model are the gas density, the radius and velocity of the shell, the gas mass and the ionization rate. The input parameter space is searched for solutions which satisfy these constraints within the allowed range. The allowed range of values for these quantities are listed in table 4.2. Based on this mode, the age of the nebula is derived to be between  $5.8 \times 10^4$ - $1.1 \times 10^5$ . The radius of the nebula is 4-6.8 pc and the density is  $(2.5\text{-}6) \times 10^4 \text{ cm}^{-3}$ . The ambient density of the ISM is constrained to be  $(1\text{-}3) \times 10^3 \text{ cm}^{-3}$  and the derived value of the ionized gas mass is  $(1\text{-}4) \times 10^4 M_{\odot}$ . The ionization rate for these solutions is  $(1\text{-}2.2) \times 10^{52} \text{ s}^{-1}$ . A star cluster of this age is too young to have formed any WR stars and hence the stellar winds arise only in OB stars. If the derived age is reliable, then the SSC powering the supernebula in NGC 5253 cannot be identified with the UV Cluster 5. Instead, this SSC must be another cluster which is optically obscured, as suggested by TBH00.

The (five) supernebulae in He 2-10 were also modelled in the same fashion. The ionization rates and gas masses of each nebula were assumed to be 0.2 times the values summarized in table 4.2. The derived age is  $(1\text{-}2) \times 10^5$  years, very similar to that derived for NGC 5253.

The age of the star clusters (specifically, of the massive stars in the clusters), assumed to be the same as that of the nebulae, is therefore  $\sim 10^5$  years. The supernebulae detected in both galaxies are powered by  $\sim 2000$  O stars. These stars are present inside a  $\sim 5 \text{ pc}$  sized region and should have been formed within a period of time short enough to avoid negative feedback.

Since, in the stellar wind-bubble model, the combined effect of all of these stars are present, this time period of formation cannot exceed  $\sim 10^5$  years. Interestingly, the typical collapse timescale of massive stars is estimated to be of this order (Stahler, Palla & Ho, 2000). Hence, the derived age of  $\sim 10^5$  years for the nebula and its ionizing stars is feasible, but only barely so (a derived value of the age larger by a factor of 2-3 would have been more comfortable). Nevertheless, if this model is reliable, then we confirm that these supernebulae are indeed the HII regions seen around the youngest massive star clusters (or SSCs) detected so far.

Whether an SSC of total stellar mass  $> 10^5 M_{\odot}$  can form all of its massive (and low mass) stars within  $\sim 10^5$  years is an issue not addressed in the literature but preliminary computations of the formation process of massive clusters has been carried out by Tan & McKee (2000). However, the analysis in this section ascribes the observed line width of  $100 \text{ km s}^{-1}$  to the bulk motion of the gas (with a value  $\sim 50 \text{ km s}^{-1}$ , directed outwards). The bulk velocity can be much less than this value if most of the kinetic energy of the gas is assumed to be undirected or turbulent. Even in such a case, a nebular age much higher than  $\sim 10^5$  years cannot be obtained. It should be noted that external confining mechanisms will also not increase the nebular age.

The age of the star cluster can be higher than  $10^5$  years if the nebular age is assumed to be longer than the dynamical age. RRL models in combination with the stellar wind-bubble scenario indicate that  $\sim 10^4 M_{\odot}$  of ionized gas would escape from the system in  $\sim 10^5$  years, implying a mass outflow rate of  $0.1 M_{\odot}/\text{yr}$ . If there is sufficient internal mass loading, i.e., if a source of gas is present inside the cluster which produces  $0.1 M_{\odot}/\text{yr}$  of gas, then the observed characteristics of the nebula can be sustained for period longer than  $10^5$  years, depending on the timescale over which mass loading is possible. A smaller scale version of such a process is known to exist in the Galactic context (see Yorke & Welz 1996; Hollenbach et al. 1994 for mass loading models and Dyson, Williams & Redman 1995 for photoevaporating disks). YSO outflows from low mass stars would probably be insufficient; for example, the mass outflow from T Tauri stars in the Orion nebula is only  $\sim 10^{-8} M_{\odot}/\text{yr}$  with a velocity of  $\sim 200 \text{ km s}^{-1}$  (Bally, O'Dell & McCaughrean, 2000). Recently discovered outflows from massive stars have large outflow rates (see for example Churchwell 1997), capable of generating  $\sim 0.1 M_{\odot}/\text{yr}$  for the star clusters modelled here. However, this outflow phase lasts for a time much shorter than  $10^5$  years and therefore cannot be utilised to prolong the lifetime of the nebulae. It is not clear whether the presence of outflows can be invoked to provide sufficient mass loading in order to prolong the lifetime of these supernebulae. Therefore, we conclude that our RRLs arise in supernebulae which are probably not significantly older than  $10^5$  years.

## 4.6 NGC 5253 and the radio-FIR correlation

The FIR luminosity and the radio luminosity of galaxies which are dominated by star formation as opposed to an AGN are very tightly correlated with an rms of  $\leq 0.2$  dex on the logarithmic scale (Condon, 1992). This radio-FIR correlation holds for several types of galaxies such as normal spirals, dwarf starbursts and dwarf irregulars (see Condon 1992). The physical reason for this correlation is not well understood in detail but may result from a chain of events involving star formation. The thermal (free-free) portion of the radio emission is from gas ionized by OB stars and the non-thermal (synchrotron) portion of the radio emission arises from the cosmic rays accelerated in SNRs, the end point of Type II SNe caused by massive stars. The

warm ( $T > 30\text{K}$ ,  $S_{60\mu\text{m}}/S_{100\mu\text{m}} \geq 1$ ) dust portion of the FIR emission arises from dust directly heated by OB stars and the cool ( $T < 30\text{K}$ ,  $S_{60\mu\text{m}}/S_{100\mu\text{m}} < 0.8$ ) dust portion of the FIR emission arises from dust heated by the diffuse interstellar radiation field. Since the FIR as well as the radio emission can thus be linked through different ways to star formation, the reason for the correlation between these two quantities is explained by this common dependence on star formation. Xu et al. (1992) have shown in the case of the LMC that the warm dust emission correlates with the thermal radio emission, while the cool dust emission correlates independently with the non-thermal radio emission. Also, the ratio of the two correlated quantities for both these independent correlations was shown to be the same as that between the the total FIR and the total radio emission strengths.

The radio continuum of most disk galaxies is dominated by non-thermal emission since the thermal fraction is typically 0.05-0.2 at 1.4 GHz (Condon, 1992). But it is known that the BCDGs have a higher fraction of thermal emission than disk galaxies: Klein & Wunderlich (1987) showed that the average radio spectral index  $\langle\alpha\rangle$  is  $-0.4$  for BCDGs, while it is  $-0.7$  for normal spirals,  $S_\nu \propto \nu^\alpha$ . Though the mean spectral index is indeed flatter for BCDGs, the dispersion in the index is much larger than for spirals and hence they did not estimate an average thermal fraction for the BCD galaxy sample. BCDGs also have a higher dust temperature (Wunderlich and Klein 1988, hereafter WK88) compared to spiral galaxies, which implies that their FIR emission is dominated by emission from warm dust. It has been suggested by Klein & Wunderlich (1987) and WK88 that the reason the BCDGs also obey the radio-FIR correlation is because this dominant warm dust emission correlates with the thermal radio emission, which is the dominant portion of the radio continuum.

NGC 5253 may well be an unique case which will help to understand the details of the radio-FIR correlation. Radio continuum flux density measurements at various frequencies using single dishes and low resolution images have shown that the radio emission of NGC 5253 is consistent with being almost purely thermal (see Beck et al. 1996 and also the spectral index map of Turner, Ho, & Beck 1998). Its total flux density at 1.4 GHz is 89 mJy (from the NVSS catalogue of Condon et al. 1998 and single-dish observations) and the FIR flux is calculated to be  $8 \times 10^8 L_\odot$  from the IRAS flux densities. From the ratio of the radio to the FIR luminosity, it can be seen that this galaxy obeys the radio-FIR correlation (Condon, 1992) to within  $1.5\sigma$ . This is a surprising result, since the non-thermal emission in this galaxy is less than 10% of the total emission at 5 GHz (Beck et al., 1996; Turner, Ho & Beck, 1998). It is known that the radio flux density and the FIR flux density of galactic HII regions are also correlated, but with a different ratio (Wynn-Williams & Becklin, 1974; Fuerst, Reich & Sofue, 1987; Broadbent, Osborne & Haslam, 1989). On the other hand, the ratio of radio to FIR flux densities of compact HII regions is not a constant, but depends on a variety of factors (Kurtz, Churchwell & Wood, 1994). Gorjian, Turner, & Beck (2001) showed that the ratio between the  $12\mu\text{m}$  flux and the thermal radio flux of the supernebula is similar to that of other star forming regions in the Galaxy and is consistent with the ratio for starburst galaxies as well. It is worth noting that though the radio emission of NGC 5253 is almost purely thermal, the radio to FIR emission ratio is similar to star forming galaxies rather than HII regions. One way to explain the correlation is the following : the dust temperature in the nucleus of NGC 5253 is high; Calzetti et al. (1995) estimated it to be 51 K. This high dust temperature is the reason why the ratio of the strength of the warm dust emission to the cool dust emission is about 16, one of the largest values known among BCDGs

and disk galaxies (Calzetti et al., 1995). Therefore we suggest that the reason NGC 5253 obeys the radio-FIR correlation is that the warm dust emission and the thermal radio emission are indeed correlated with each other, and the ratio between these two quantities is the same as that between the total FIR and total radio in normal spirals, as suggested by Xu et al. (1992) and WK88. WK88 had also put forward an alternative explanation for BCDGs obeying the radio-FIR correlation. They had suggested that a possible lower dust fraction in these galaxies would compensate for the lower non-thermal radio fraction. This explanation is unlikely for NGC 5253, since among all BCDGs, it has the lowest non-thermal fraction but the highest dust to gas ratio (Lisenfeld & Ferrara, 1998).

## 4.7 Summary

We have detected the  $H92\alpha$  recombination line from two dwarf starbursts NGC 5253 and He 2-10. The line emitting gas in both galaxies is found to be of densities  $\sim 10^4 \text{ cm}^{-3}$  with a size of 2-10 pc, implying an  $N_{\text{Ly}\alpha}$  of a few times  $10^{52} \text{ s}^{-1}$ . Though the line emission is spatially unresolved and the linear size of the beam area corresponds to 150 pc and 315 pc respectively for NGC 5253 and He 2-10, we present arguments to show that the line emission is compact (few parsecs). Based on the derived parameters, these lines seem to originate from gas ionized by optically obscured SSCs in both galaxies. These ‘supernebulae’ around these clusters have been detected in radio continuum emission and we show that these nebulae are capable of producing all the observed line emission in both the galaxies. Hence we identify the line emitting objects with these supernebulae. Both the detection of RRL emission as well as direct radio continuum imaging of these ‘supernebula’ around SSCs pose problems about the lifetimes and dynamics of the ionized gas. Using a stellar wind-bubble model, we derive the nebular age to be  $(0.6-1) \times 10^5$  years. Hence we conclude that the observed RRLs arise in HII regions around the youngest SSCs known so far.

Finally, we point out that though NGC 5253 has a thermal radio spectrum, it seems to obey the radio-FIR correlation, which is known to hold for galaxies dominated by non-thermal radio emission. This feature may well be evidence for the warm dust portion of the FIR emission to be correlated with the thermal radio emission, independent of the cold dust FIR emission and the non-thermal radio emission, as suggested by Xu et al. (1992).