VLA H53α OBSERVATIONS OF THE CENTRAL REGION OF THE SUPER STAR CLUSTER GALAXY NGC 5253

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ABSTRACT

We present observations in the H53α line and radio continuum at 43 GHz carried out with the VLA in the D configuration (2" angular resolution) toward the starburst galaxy NGC 5253. VLA archival data have been reprocessed to produce a uniform set of 2, 1.3, and 0.7 cm high angular (0.2" × 0.1") radio continuum images. The radio recombination line (RRL) H53α, a previously reported measurement of the H92α RRL flux density, and the reprocessed high angular resolution radio continuum flux densities have been modeled using a collection of H α regions. Based on the models, the ionized gas in the nuclear source has an electron density of ~6 × 10^4 cm^-3 and a volume filling factor of 0.05. A Lyman continuum photon production rate of 2 × 10^52 s^-1 is necessary to sustain the ionization in the nuclear region. The number of required O7 stars in the central 1.5 pc of the supernebula is ~2000. The H53α velocity gradient (10 km s^-1 arcsec^-1) implies a dynamical mass of ~3 × 10^3 M☉; this mass suggests that the supernebula is confined by gravity.

Subject headings: galaxies: starburst — radio lines: general

1. INTRODUCTION

NGC 5253 is a blue dwarf irregular galaxy (located at ~4 Mpc; Saha et al. 1995) with an infrared luminosity of ~2 × 10^9 L☉ (Beck et al. 1996). NGC 5253 hosts several groups of young star clusters, called super star clusters (SSCs) (Gorjian 2001; Calzetti et al. 1997). The optical spectrum of NGC 5253 shows signatures of large numbers of Wolf-Rayet (WR) stars (Campbell et al. 1986; Walsh & Roy 1989; Schaerer et al. 1997). A nearly flat radio continuum spectra (see Fig. 1) also indicates that free-free emission is the dominant emission mechanism and that NGC 5253 is a young starburst galaxy.

The VLA observations made with similar angular resolution (1"–2") at 6, 3.6, and 2 cm (Beck et al. 1996; Turner et al. 1998) reveal a complex structure in the central 20" × 40" region, dominated by a compact source (≤1", 1" ~ 15 pc). VLA observations of NGC 5253 made with higher angular resolution at 1.3 (0.33" × 0.12") and 2 cm (0.22" × 0.08") reveal two compact sources. The main source has a deconvolved angular size of 0.10" × 0.05", which corresponds to ~1–2 pc (Turner et al. 2000). NICMOS observations show the presence of a double cluster in the nucleus of the galaxy separated by 6–8 pc (~0.5") (Alonso-Herrero et al. 2004), which may be related to the double radio nebula detected by Turner et al. (2000). Higher angular resolution observations at 0.7 cm (74 × 17 mas) show that the stronger component of the double nebula is compact, but partially resolved at scales of 0.05" (Turner & Beck 2004). The main compact radio source (Turner et al. 1998) was named “the supernebula.” Beirao et al. (2006), based on mid-IR Spitzer observations from NGC 5253, report that mid-IR emission is dominated by an unresolved cluster coincident with the compact supernebula. Beirao et al. (2006) also observed an anticorrelation between PAH strength and UV radiation, suggesting destruction of PAH molecules in the central region.

Based on 1.3 and 2 cm wavelength observations, Turner et al. (1998) propose that the dominant radio source is a strong candidate for a globular cluster in the process of formation. The supernebula is visible at radio and infrared frequencies with no obvious optical counterpart. This supernebula is partially optically thick at 2 cm with an electron density of ~4 × 10^4 cm^-3 (Meier et al. 2002), a density typical of compact young (~10^5 yr) H ii regions in our galaxy (Wood & Churchwell 1989). Radio and infrared observations require a Lyman continuum flux of 4 × 10^52 s^-1, equivalent to a few thousand O7 stars (Gorjian et al. 2001). Infrared Br α and γ recombination line observations revealed that the gas in the nebula is potentially bound by gravity (Turner et al. 2003). Based on 0.7 cm wavelength observations, Turner & Beck (2004) confirm that the supernebula is a giant compact H ii region that is gravitationally bound. In order to reproduce the radio continuum emission, the nebula requires the excitation of ~4000 O7 stars within the central 5 pc region (Turner et al. 2000).

In this paper, we present observations of the RRL H53α toward NGC 5253 using the VLA. The H53α RRL provides information about the physical properties of the optically thin ionized gas in the supernebula. In § 2, the technical details of the observations are presented. In § 3, we present the results, while in § 4, we provide the discussion. In § 5, we present the summary.

2. VLA OBSERVATIONS

2.1. H53α Line.

The H53α line (νrest = 42951.9 MHz) was observed in the D configuration of the VLA on 2004 May 31 and June 2, 11, 12, and 13. We used observation cycles with integration times of 10 minutes on NGC 5253 and 1 minute on the phase calibrator J1316–336 (J2000.0) (~1.5 Jy displaced by 6°). Two frequency windows (LOs), centered at 42885.1 and 42914.9 GHz, were used to observe the RRL H53α. For each frequency window, the on-source integration time was ~2 hr, using a mode of 15 spectral channels with a channel separation of 3.125 MHz (~22 km s^-1). The data calibration was carried out for each frequency window using the continuum channel, consisting of the central 75% of the band. The flux density scales were determined from observations of J1331+305 (3C 286; 1.47 Jy). The bandpass response of the
instrument was corrected using observations of J1337−129 (~9.5 Jy). The parameters of the observations are summarized in Table 1. The coordinates listed in this table correspond to the center of the observations. In order to reliably track the phase variations introduced by the troposphere, the calibration of the data was performed by first correcting for the phases, and subsequently correcting for both amplitude and phase. The line data cubes were Hanning-smoothed to reduce the Gibbs effect, and the final velocity resolution was ~44 km s⁻¹. The line data were further calibrated using the solutions obtained by self-calibrating the continuum channel of each frequency window. The radio continuum images were obtained by combining the continuum channels of each frequency window using the task `DBCON` from AIPS, and the self-calibration method was also applied to this combined data. The continuum emission was subtracted for each frequency window using the AIPS task `UVLSF` with a zero-order polynomial fit based on the line-free channels. The H53α line cubes and the 43 GHz continuum image were made using a natural weighting scheme, and then convolved to obtain a circular Gaussian beam of 2.0″ (P.A. = 0°). The combination of the different frequency windows was carried out following a method similar to that used for the H53α line observed toward M82 (Rodríguez-Rico et al. 2004); the two line cubes were combined into a single line cube after regridding in frequency the line data for each frequency window. This process was carried out using the GIPSY reduction package, and a total of 19 velocity channels were obtained after putting together the two LO windows. The total line bandwidth, after combining all the windows, is about 60 MHz (400 km s⁻¹).

### 2.2. Radio Continuum at 2, 1.3, and 0.7 cm

In addition to the continuum emission at 0.7 cm, obtained from the line-free channels of the H53α line observations (at angular resolution of 2.0″), we have included archive continuum data in the analysis. VLA continuum observations at 2, 1.3, and 0.7 cm have been reprocessed from the VLA archive and used here to determine the properties of the continuum of the nuclear regions of NGC 5253 over angular scales less than 7″. The observations at 2 and 1.3 cm were made with the A configuration of the VLA on 1998 April 9 (Turner et al. 2000). The observations at 0.7 cm were made with the VLA in the A configuration including Pie Town on 2002 March 9 (Turner & Beck 2004). The phase calibrator for the 0.7 cm is J1316−336. Absolute flux density calibration for all the 2, 1.3, and 0.7 cm observations was based on observations of 3C 286. The data at the three frequencies were brought to the same angular resolution by suitable choices of both weighting in the u-v plane and u-v range selection. The final angular resolution of all three images is 0.2″ × 0.1″ (P.A. = 0°).

### 3. RESULTS

Figure 1 shows a spectrum made with the low angular resolution (≥2") observations summarized in Table 2. These low angular resolution observations refer to the whole of the nucleus of NGC 5253. This spectrum is nearly flat in the frequency range 1–230 GHz. As noted before by Meier et al. (2002), a single component that consists of optically thin free-free extended emission ($S \propto \nu^{-0.75}$) does not explain the observed flux densities at frequencies ≥10 GHz. An optically thick free-free component with an electron density of ~6 × 10⁴ cm⁻³ is necessary to explain the observed flux densities in the frequency range of 1–230 GHz; this optically thick free-free component has a turnover frequency at ~9 GHz. The electron density value of the compact ionized gas component was obtained based on high angular resolution radio observations, and the fit is described in § 4.2. There are at least three nonthermal components with angular sizes between 1″ and 4″, which only contribute about 2 mJy at 6 cm and 1 mJy at 2 cm (see Turner et al. 1998). Turner et al. (1998) report three nonthermal sources based on observations at 2 and 6 cm, located near to (east, southeast, and northwest of) the central super star cluster. Thus, a third nonthermal ($S \propto \nu^{-0.75}$) component with $S_0 = 2$ mJy has also been used in the fit of the total continuum emission shown in Figure 1. The flux density level of the extended optically thick component is fit to the flux density values obtained from subtraction of the optically thick free-free component and the synchrotron emission from the observed total flux densities.

Figure 2 shows the 43 GHz radio continuum observations carried out in the D configuration of the VLA (2″ angular resolution). The integrated 43 GHz continuum flux density measured at this angular resolution is 45 ± 4 mJy. The radio continuum emission at 43 GHz extends ~30″ in the north-south direction and ~10″ in the east-west direction.

### Table 1

| Parameter                              | H53α RRL (43 GHz) |
|----------------------------------------|-------------------|
| Right ascension (J2000.0)              | 13°39′55.96″      |
| Declination (J2000.0)                  | −31°38′24.38″     |
| P.A. (deg)                             | 0                 |
| On-source observing duration (hr)      | 8                 |
| Bandwidth (MHz)                        | 60                |
| Total number of spectral channels      | 19                |
| Optical heliocentric velocity $V_H$ (km s⁻¹) | 397              |
| Velocity coverage (km s⁻¹)             | 400               |
| Velocity resolution (km s⁻¹)           | 44                |
| Amplitude calibrator                   | J1331+305         |
| Phase calibrator                       | J1316−336         |
| Bandpass calibrator                    | J1337−129         |
| rms line noise per channel (mJy beam⁻¹) | 0.4              |
| rms, continuum (mJy beam⁻¹)            | 0.2              |
of the 43 GHz continuum peak. The angular resolution is 2\".

Table 2

| Wavelength (cm) | Flux Density (mJy) | Angular Resolution (arcsec) | Reference |
|----------------|--------------------|-----------------------------|-----------|
| 20 .............| 56 ± 1             | 9 × 2\"                      | 1         |
| 6 ..............| 46 ± 1             | 2.2 × 1.4"                   | 1         |
| 3.6 ...........| 40 ± 6             | 2.2 × 1.4"                   | 2         |
| 2 ..............| 51 ± 1             | 2.2 × 1.4"                   | 1         |
| 1.3 ...........| 9.3 ± 1            | 0.2 × 0.1"                   | 3         |
| 0.7 ...........| 11 ± 1             | 0.2 × 0.1"                   | 3         |
| 0.31 ..........| 47 ± 4             | 2"                          | 3         |
| 0.26 ..........| 9.5 ± 1            | 0.2 × 0.1"                   | 3         |
| 0.13 ..........| 54 ± 5             | 0.9 × 0.6"                   | 4         |
| 0.10 ..........| 52 ± 4             | 14.0 × 6.5"                  | 5         |
| 0.03 ..........| 46 ± 10            | 6.5 × 4.5"                   | 4         |

a Values were obtained by integrating over the central 20\" × 40\" region and used to obtain the total radio continuum spectrum (Fig. 1). All values were obtained from the literature except the value at 0.7 cm.

b Values were obtained from the reprocessed VLA data (see § 2.2), integrating over the inner 0.4\". These values were used in the models of a collection of H\textsc{ii} regions (Fig. 6).

References.—(1) Turner et al. 1998; (2) Mohan et al. 2001; (3) this paper; (4) Meier et al. 2002; (5) Turner et al. 1997.

![Radio Continuum Image of NGC 5253 at 43 GHz](image)

Fig. 2.—Radio continuum image of NGC 5253 at 43 GHz obtained using the VLA in the D configuration. Contour levels are drawn at −3, 3, 5, 10, 20, 30, 40, 60, 80, and 90 times the rms of 0.13 mJy beam\(^{-1}\). The cross shows the position of the 43 GHz continuum peak. The angular resolution is 2\".

![Channel Images of the H53\alpha Line Emission](image)

Fig. 3.—Channel images of the H53\alpha line emission (contours) toward NGC 5253 obtained using the VLA in the D configuration. Contours are −3, 3, 4, 5, 6, 7, and 8 times 0.4 mJy beam\(^{-1}\), the rms noise. The cross shows the position of the 43 GHz continuum peak. The synthesized beam (2\") is shown in the top left panel. The central heliocentric velocity is listed for each image.

Fig. 3 shows the H53\alpha line velocity channel images of NGC 5253 at an angular resolution of 2\". The H53\alpha line emission is observed in the heliocentric velocity range ∼340−450 km s\(^{-1}\). The peak H53\alpha line flux density is ∼3.6 mJy beam\(^{-1}\). The deconvolved angular size measured in the H53\alpha line is ∼1.0\". We have obtained the 1.6 \( \mu \)m NICMOS image from the Hubble Space Telescope (HST) archive in order to compare the H53\alpha RRL with the IR emission; the plate scale of the NICMOS observations is 0.034\". Following Turner et al. (2003), we have assumed that the brightest source in the 1.6 \( \mu \)m NICMOS image can be identified with the radio peak as observed at an angular resolution of 2\". We thus have shifted the NICMOS image by ∼1\" in the northeast direction in order that the IR and radio peaks coincide, which is consistent with the astrometrical precision of HST. Figure 4 shows the overlay of the integrated H53\alpha line emission on the 1.6 \( \mu \)m NICMOS image after shifting the IR image. The integrated H53\alpha line (0.31 ± 0.03 Jy km s\(^{-1}\)), as obtained from a
Gaussian fit, has a peak line flux density $S_L = 5.3 \pm 0.6 \text{ mJy}$, a FWHM of $58 \pm 12 \text{ km s}^{-1}$, and a central heliocentric velocity of $397 \pm 5 \text{ km s}^{-1}$. The velocity-integrated H53$\alpha$ line emission is shown in Figure 5.

4. DISCUSSION

4.1. Total Radio Continuum Emission

The spatially integrated radio continuum flux density obtained with low angular resolution, $S_{43 \text{ GHz}} \approx 45 \text{ mJy}$ is comparable with previous measurements from interferometric observations carried out in the wavelength range of $21-0.13 \text{ cm}$ (1.4-230 GHz). Previous observations have revealed that the radio continuum emission at $43 \text{ GHz}$ is dominated by thermal free-free emission (Beck et al. 1996), and our $43 \text{ GHz}$ radio continuum observations suggest that the contribution from nonthermal emission is negligible at wavelengths shorter than $6 \text{ cm}$ (>5 GHz; see Fig. 1). Thus, no contribution from synchrotron sources will be considered in the radio continuum emission models (see § 4.2).

4.2. Models of a Collection of H ii Regions

Models that consist of H ii regions have been used to estimate the electron density of the ionized gas in starburst galaxies like M82 (Rodríguez-Rico et al. 2004), NGC 253 (Rodríguez-Rico et al. 2006) and Arp 220 (Anantharamaiah et al. 2000; Rodríguez-Rico et al. 2005). The models are constrained by (1) the physical diameter of the region associated with the RRL emission and (2) the measured radio continuum and RRL flux densities. The RRLs H92$\alpha$ (Mohan et al. 2001) and H53$\alpha$ are used, along with the high angular resolution radio continuum observations described in § 2.2, to estimate the electron density of the ionized gas in NGC 5253.

Based on the high angular resolution VLA archival observations ($0.2'' \times 0.1''$) described in § 2.2, the deconvolved angular size of the compact nuclear region is $\sim 0.1''$ ($\sim 1.5 \text{ pc}$). The peak position measured in these high angular resolution radio continuum images agrees with the peak position of the RRLs H53$\alpha$ and H92$\alpha$ (Mohan et al. 2001). Thus, it is assumed that the H53$\alpha$ and the H92$\alpha$ RRLs arise from the same $\sim 1.5 \text{ pc}$ ($\sim 0.1''$) region.

The radio continuum flux densities, at $0.2'' \times 0.1''$ angular resolution, are $S_{0.2'' \text{ cm}} = 9.3 \pm 1$, $S_{0.3'' \text{ cm}} = 11 \pm 1$, and $S_{0.7'' \text{ cm}} = 9.5 \pm 1 \text{ mJy}$. The velocity-integrated H53$\alpha$ and H92$\alpha$ line emission are $50 \text{ mJy km s}^{-1}$ and $203 \text{ mJy km s}^{-1}$, respectively. Acceptable models are those that can reproduce the continuum flux densities and the velocity-integrated line emission on both RRLs. Based on the size measured in the radio continuum images, the maximum volume that this collection of H ii regions may occupy is the volume of a spherical $1.5 \text{ pc}$ region.

Following the procedure listed in Rohlfs & Wilson (1996, pp. 248–249), we use models that consist of H ii regions ionized by O7 early-type stars ($10^{49}$ Lyman continuum photons s$^{-1}$). The emission measure of each H ii region is $EM_e = 2n_e^2l$. The continuum optical depth (Altenhoff et al. 1960) is

$$\tau_c = 8.235 \times 10^{-2} \left( \frac{T_c}{1 \text{ K}} \right)^{-1.35} \left( \frac{\nu}{1 \text{ GHz}} \right)^{-2.1} \left( \frac{EM}{1 \text{ cm}^{-6} \text{ pc}} \right),$$

and the blackbody radiation is defined by

$$\frac{B_\nu}{1 \text{ mJy}} = 3.07 \times 10^7 \left( \frac{\nu}{1 \text{ GHz}} \right)^2 \left( \frac{T_c}{K} \right).$$

The electronic temperature of the thermally ionized gas is assumed to be $T_e = 10^4 \text{ K}$, and $\nu$ is the frequency. The radio continuum flux density ($S_{\text{ch}}$) for each H ii region in the models is given by

$$\frac{S_{\text{ch}}}{1 \text{ mJy}} = \left( \frac{B_\nu}{1 \text{ mJy}} \right) \left( \frac{\Omega}{1 \text{ sr}} \right) (1 - e^{-\tau_c}),$$

where $\Omega = \pi (l/4.0 \text{ Mpc})^2$ is the solid angle subtended by the H ii region.
The models for RRL emission take into account deviations from local thermodynamic equilibrium (LTE) using the departure coefficients $b_n$ and $\beta_n$. The peak line flux density is
\[
\frac{S_L}{1 \text{ mJy}} = \left( \frac{B_\nu}{1 \text{ mJy}} \right) \left( \frac{\Omega}{1 \text{ sr}} \right) \times \left[ \frac{\tau_c + b_n \tau_L}{\tau_c + \tau_L} \right] \left( 1 - e^{-\tau_c} \right) - \left( 1 - e^{-\tau_L} \right),
\]
where $\tau_c = \tau_c r$ is the line optical depth in LTE and $\tau_L = \tau_c r b_n \beta_n$ is the non-LTE line optical depth. The line-to-continuum ratio $r$ is defined by
\[
r = 2.33 \times 10^4 \left( \frac{\Delta \nu}{1 \text{ kHz}} \right)^{-1.0} \left( \frac{\nu}{1 \text{ GHz}} \right)^{2.1} \left( \frac{T_e}{1 \text{ K}} \right)^{-1.15} \frac{\text{EM}_L}{\text{EM}_C}.
\]
In this equation, the line width is $\Delta \nu$, and $\text{EM}_L = 0.9\text{EM}_C$ is the emission measure of the line, assuming a fractional number abundance of He$^+$ to H of 0.1.

The electron density of the ionized gas in these models was varied between $10^2$ and $10^6$ cm$^{-3}$. Figure 6 shows the results from single-density models that fit the radio continuum and RRL observations for NGC 5253. The solution for the electron density obtained from the models is $\sim 6 \times 10^4$ cm$^{-3}$. This electron density is comparable to the derived value of $4-5 \times 10^4$ cm$^{-3}$ (Turner et al. 2000; Meier et al. 2002). The total volume filling factor of the dense ionized gas is $\sim 0.05$, and the total area filling factor is $\sim 0.95$. Based on the results of the single density models, the Lyman continuum needed to ionize the 1.5 pc region is $\sim 2 \times 10^{52}$ s$^{-1}$, corresponding to $\sim 2000$ O7 stars. The total mass of O7 stars, assuming a mass of 20 $M_\odot$ for each O7 star (Herrero et al. 1992), is about $4 \times 10^4$ $M_\odot$.

Comparison of the velocity field observed in the H53$\alpha$ line from NGC 5253. Contour levels are the heliocentric velocities at 380, 390, 400, 410, and 420 km s$^{-1}$. The gray scale shows the heliocentric velocity field image in the H53$\alpha$ line. The white cross shows the peak of the 43 GHz continuum emission. The HPFW is 2$''$. The dust extinction in the infrared at 1.6 $\mu$m (Fig. 4) suggests that the radio supernebula is gravitationally bound. The mass implied by the velocity gradient is consistent with the luminosity implied by starburst models with this $N_{13c}$ (Leitherer et al. 1999). The H53$\alpha$ line FWHM of 58 $\pm$ 5 km s$^{-1}$ confirms that the supernebula is gravity bounded. The difference in the line widths is interpreted as the contribution of the extended ionized gas component to the Br$\gamma$ and H92$\alpha$ lines, compared to the H53$\alpha$ line, which traces mostly the compact ionized gas component.
5. CONCLUSIONS

The H$\alpha$ line and the radio continuum emission at 43 GHz were observed with the VLA in the D configuration toward the galaxy NGC 5253. VLA archival data were reprocessed to produce a uniform set of 2, 1.3, and 0.7 cm continuum images with angular resolution of $0.2'' \times 0.1''$. Using a single-density model to reproduce the observed radio continuum at 2, 1.3, and 0.7 cm, as well as the H$\alpha$ and H$\beta$ RRL emission in the central compact region ($\sim 1.5$ pc), the average electron density of the ionized gas is calculated as $1.6 \times 10^4$ cm$^{-3}$. The 43 GHz radio continuum emission arises from an optically thin, free-free emission source. The Lyman continuum photon rate of $2 \times 10^{52}$ s$^{-1}$ is necessary to sustain the ionization in the 1.5 pc in the inner region of the galaxy NGC 5253, which contains $\sim 2000$ O7 stars. The peak of the H$\alpha$ line emission coincides with the brightest source observed in the 1.6 $\mu$m IR image to within 1''. The velocity gradient measured in the H$\alpha$ line (10 km s$^{-1}$ arcsec$^{-1}$), if interpreted as rotation, implies a dynamical mass of $3 \times 10^6 M_\odot$ within the central 20 pc. The rough agreement of the mass derived from the apparent rotation with the mass estimated from the observed Lyman continuum rate, $N_{Lyc}$, suggests that the gas motion within the supernebula is governed by gravity.

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