The Radio Super Nebula in NGC 5253

Jean L. Turner[1]

Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095-1562

turner@astro.ucla.edu

Sara C. Beck[2]

Department of Physics and Astronomy, Tel Aviv University, Ramat Aviv, Israel

sara@wise1.tau.ac.il

and

Paul T. P. Ho[3]

Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

Received ______________________; accepted ______________________

ABSTRACT

We present 1 cm and 2 cm sub-arcsecond resolution VLA images of the dwarf galaxy NGC 5253. Within the central starburst, we detect high brightness (T_b(2cm) $\sim$ 100-11000 K) radio continuum sources. These appear to be very dense, "compact" HII regions. The dominant radio source is a nebula $\sim$1-2 parsec in size, requiring several thousand O stars within the volume to maintain its ionization. This nebula has no obvious optical counterpart. The exciting cluster is nearly two orders of magnitude larger than indicated by Hα fluxes and accounts for a significant fraction of the infrared luminosity of the galaxy. This cluster is a strong candidate for a globular cluster in the process of formation, perhaps the youngest globular cluster known.

Subject headings: galaxies: individual (NGC 5253) — galaxies: starburst — galaxies: star clusters — galaxies: dwarf — galaxies: peculiar — radio continuum: galaxies

1. Introduction

NGC 5253 is a dwarf I0/S0 galaxy undergoing a starburst of infrared luminosity $L_{IR} \sim 2 \times 10^9$ $L_\odot$ (Beck et al. 1996). The starburst in NGC 5253 is very young, displaying the optical (Gorjian 1996; Calzetti et al. 1997) and infrared (Rieke, Lebofsky, & Walker 1988) signatures of a starburst no more than a few million years old. Its radio continuum emission is unique among galaxies for being almost entirely thermal (Beck et al. 1996), which suggests that the star formation has not persisted for the time it takes to produce a significant number of supernovae.

Radio observations at 6, 3.6, and 2 cm made with the NRAO [1] Very Large Array with 1-2″ resolution indicated that the radio free-free emission in NGC 5253 is partly optically thick at cm wavelengths (Turner et al. 1998). Classical Galactic HII regions such as Orion are optically thick at wavelengths around 1 meter; the high densities needed for a source to be optically thick at 2 cm are seen in the Galaxy only in the youngest ultra-compact HII regions, of diameter ∼0.01 pc (Habing & Israel 1979; Wood & Churchwell 1989). Thermal sources of this size cannot be detected in other galaxies (Turner & Ho 1994). The radio continuum emission in NGC 5253 is an order of magnitude stronger than predicted by the observed Hα emission (Calzetti et al. 1997), indicating that the extinctions are substantial, another indication of youth. This is very likely the location of the youngest part of the starburst, which is optically invisible.

To minimize the possibility of confusion by sources with different optical depths or synchrotron emission in the same beam we reobserved the radio core of NGC 5253 at 2 cm with the A configuration of the VLA, which gives a synthesized beam of 0.1″- 0.3″ in size. We also extended the spectrum to 1 cm. It is on these observations that we report in this paper.

2. Observations

The 2 cm and 1.3 cm ("1 cm") observations were made with A configuration of the VLA on 13 October 1998. Absolute flux calibration was based on observations of 3C286, and is good to better than 5%. Phase center was at $\alpha = 13^h\ 39^m\ 55.84^s$, δ = -31° 38′ 29.1″ (J2000). The naturally- weighted synthesized beams are 0.22″ × 0.08″ (FWHM)

---

[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

at p.a. -8° for the 1 cm map, and $0.33'' \times 0.12''$ at p.a.=1.9° for the 2 cm map. The north-south elongation of the beam is caused by the foreshortening of the array, due to the southerly declination of the source. The two bands have different sensitivities to lower spatial frequencies so we cannot directly compare total fluxes nor compute spectral indices from the maps. Because of the lack of short spacings, the 2 and 1 cm maps are sensitive only to structures $\lesssim 2''$ -$4''$ in the east-west direction and $\lesssim 4$ -$8''$ north-south.

These observations were designed to determine brightness temperatures and the structure and nature of compact radio sources rather than total fluxes, which are available from lower resolution observations (Turner et al. 1998). There was insufficient signal-to-noise for self-calibration without significant loss of spatial resolution, and so the measured source sizes may be broadened by seeing at the fractional arcsecond level, with a more pronounced effect expected at 1 cm. We calculate from comparison with lower resolution maps (Turner et al. 1998) that our 2 cm maps resolve out ~50% of the total emission within the central $20'' \times 40''$, although they appear to recover all of the 2 cm emission in the inner $6'' \times 6''$ (Beck et al. 1996). The images were deconvolved from the dirty beams using the CLEAN algorithm. The 3σ rms noise levels in the continuum maps are 0.09 and 0.11 mJy/beam for 2 cm and 1 cm, respectively.

3. The Super Nebula and its Environs

In Figure 1 we display the 1.3 and 2 cm VLA maps of the central $3''$ (50 pc) of the starburst in NGC 5253. The maps show a dominant radio continuum source at both 2 and 1 cm. Weaker sources appear to the north and east of the main radio nebula. The sources appear elongated in the north-south direction, which is mostly due to the north-south elongation of the synthesized beam. In Figure 2, the 1 cm map is superimposed on the Hα image of Calzetti et al. (1997) . The dominant radio source does not have an obvious counterpart in the Hα image. Given the high ($A_v \sim 35$ mag) extinction (Calzetti et al. 1997) estimated for the region, it is unlikely that the Hα traces these high density nebulae at all.

The position of the dominant radio source is $\alpha = 13^h39^m55.964^s$, δ = -31° 38′ 24.″ 38, in agreement with lower resolution images (Turner et al. 1998). The absolute positions are known to the ∼0.01″ accuracy of the phase calibrator; and relative positions to 0.002-.005″, based on the signal to noise. The 1 cm map has a secondary peak at 55.982^s, 24.37″. This peak is not evident at 2 cm. There is also either a separate source or an extension of the main source northwards by ∼1″, which is apparent in both maps but stronger at 2 cm.

The main source is slightly resolved. The size of the source, deconvolved from the beam assuming a Gaussian source, is 0.10″ × 0.04″ ± 0.02″ (FWHM), at p.a. 27° ± 7°, or about 2 pc × 1 pc for an adopted distance of 4 Mpc (Saha et al. 1995). The peak flux fitted to the core is 11 ± 1 mJy/beam, with the uncertainty largely due to the difficulty of fitting the compact source properties within the lower level extended emission. The observed brightness temperature is therefore ∼11000K ± 4000K, close to the value of electron temperature determined for the visible HII regions in NGC 5253, which is ∼11000-12000K (Campbell, Terlevich, & Melnick 1986; Walsh & Roy 1989; Kobulnicky et al. 1997). This indicates that the free-free emission has a significant optical depth at 2 cm ($\tau \sim 1$). The total flux estimate for the central 3″ mapped region is ∼22 mJy at 2 cm, in agreement with lower resolution observations (Beck et al. 1996; Turner et al. 1998).

At 1 cm, the peak flux density for the main source is 9 ± 1 mJy/beam. The observed brightness temperature of this source is 3900K, given the source size measured at 2 cm. Since the 1 cm map may be affected by seeing, the true peak flux density may actually be higher. It may also be that the spectrum is turning over, and that the source is becoming optically thin at 1 cm. The total flux density of this source at 1 cm is 20 mJy. Since the

1 cm map is more affected by undersampling than the 2 cm map, we cannot determine a reliable spectral index. However, it is clear that the spectrum is approximately flat, and that the turnover frequency of the free-free emission is about 22 GHz. The flat spectrum appears to rule out supernova remnants or radio supernovae as the source of the emission.

The eastern source in the 1 cm image has a peak flux density of ∼1.4 mJy/beam, nearly 3 times higher than the 2 cm flux density of ∼0.5 mJy/beam. The minimum brightness temperature is 100K. The source appears to have a spectrum that is still rising at 22 GHz. If a rising spectrum is an indication of youth, as we argue below, then this may be the very youngest part of the young part of the starburst in NGC 5253.

4. Excitation of the Super Nebula

Since the compact source is at least partly optically thick, nebular quantities such as the Lyman continuum rate, $\mathrm{N_{Lyc}}$, that are derived directly from the radio fluxes assuming optically thin emission may underestimate the true Lyman continuum rates. However since the spectrum appears to be turning over at about 1 cm, the emission is not very thick and the optically thin assumption at these high frequencies yield a reasonable estimate of $\mathrm{N_{Lyc}}$. The "optically thin" estimates are $\mathrm{N_{Lyc}^{thin}} = 8.8 \times 10^{49}$ $(\mathrm{D/Mpc})^2$ $\mathrm{S_{mJy}^{2\,cm}} = 3 \times 10^{52}$ s^{-1} for the dominant source, and $\mathrm{N_{Lyc}^{thin}} =$ 2-3 $\times\ 10^{51}$ s^{-1} for the eastern 1 cm source.

$\mathrm{N_{Lyc}}$ can also be estimated from the size and emission measure of optically thick HII regions, since $\mathrm{N_{Lyc}} = n_e^2 V$ for an ionization-bounded nebula, and the emission measure, $\mathrm{EM} = \int n_e^2 dl$ and source area (hence volume) can be determined from the radio data. The turnover frequency, ν_t where the free-free spectrum changes from optically thick to thin, is related to the emission measure via $(\mathrm{EM/cm^{-6}\ pc}) = 12.1\ (\nu_t/\mathrm{GHz})^{2.1}\ T_e^{1.35}$ (Mezger & Henderson 1967). Since the turnover frequency, ν_t, of the central source appears to be ∼22

GHz, EM $\sim$ 2-3 $\times$ 10^9 cm^{-6} pc. The size of the nebula is determined to be 2 pc $\times$ 1 pc from the 2 cm map. If we assume the line of sight dimension is similar, an rms electron density of $< n_e^2 >^{1/2} \sim 4 \times 10^4$ cm^{-3} obtains, which is high for an HII region of this size. The implied mass of ionized gas in this nebula is 6600 M$_\odot$.

Based on our estimate of n_e^2 V, we find the "optically thick" Lyman continuum rate required to ionize the volume of high density gas is $\mathrm{N}_{\mathrm{Lyc}}^{\mathrm{thick}} \sim 4 \times 10^{52} s^{-1}$. This is about 70 times higher than what would be predicted on the basis of Hα fluxes (Calzetti et al. 1997). However, our $\mathrm{N}_{\mathrm{Lyc}}$ is within a factor of two of the observed Brackett line flux (Kawara, Nishida, & Phillips 1989) prediction (Beck et al. 1996).

5. The Radio Super Star Cluster Nebula

We have estimated that the Lyman continuum rate for this nebula is $\sim 4 \times 10^{52}$ s^{-1}. We have assumed an ionization bounded nebula; if the nebula is density bounded $\mathrm{N}_{\mathrm{Lyc}}$ will be higher. If we assume that the average OB star is an O7 star, the number of O7 stars required to excite the nebula is 4000. These stars must be located within a $\sim$ 1-2 pc diameter region, or else the ultraviolet excitation requirements are even more extreme. For a Salpeter IMF (which seems to hold for 30 Doradus: Massey & Hunter (1998)), with an upper mass cutoff of 40-50 M$_\odot$, and lower mass cutoff of 1 M$_\odot$, this $\mathrm{N}_{\mathrm{Lyc}}$ would correspond to $\sim 10^5$ stars. The size and deduced stellar mass of the cluster exciting this nebula are characteristic of super star clusters (SSCs) seen in many intense starbursts including NGC 5253 (Meurer et al. 1995). Most of the SSCs seen in the optical and ultraviolet in NGC 5253 are not associated with radio sources (Gorjian 1996). This is probably because the youngest clusters which are most likely to have the densest gas and the bright radio nebulae are also most likely to be highly obscured.

The infrared luminosity implied by this ionization rate is $\sim 7\times10^{-44}$ $L_\odot/N_{Lyc}= 2\times\ 10^9$ $L_\odot$ for a zero age cluster with an IMF extending to 1 $M_\odot$. The observed IRAS fluxes give a luminosity of 1.8×10^9 $L_\odot$. Our numbers are just consistent with the IRAS luminosity, which includes the entire galaxy and not just this cluster. What are the possible explanations for the low L_{IR}/N_{Lyc} ratio?

We do not have a definite answer to this question; this is the first source of this type to be observed. The combination of an extremely intense radiation field and high gas density in a very compact volume put this source far outside the usual relation between gas, dust and stellar population which is reflected in the "normal" L_{IR}/N_{Lyc} (Genzel et al. 1982, e.g.) ratio. It could be that the IMF is exceedingly top-heavy. There are possibly other energy sinks within this nebula in addition to dust. Since the nebula is very young, it may be that transient mechanisms are involved. For example, dissociation of the surrounding molecular clouds and shocks are possible sinks of energy. A 10^8 $M_\odot$ molecular cloud of H_2 molecules would last $\sim 10^4$ yrs at the current rate of 3×10^8 $L_\odot$, at 4.5 ev per dissociation. Dissociation of molecular clouds is thus not a viable long term energy sink, but could well be operating in the short term in an extremely young source. Other sources of energy dissipation include winds and shocks, for which there is ample evidence (Martin & Kennicutt 1995; Marlowe et al. 1995; Calzetti et al. 1999). Another alternative to additional energy sinks is that there may be additional ionization sources within the nebula, ionization sources that have significantly less total luminosity for a given ionization. A possible non-stellar ionization source is an AGN. We cannot with these observations rule out the possibility that the ionization source is a mini-AGN, although there is little spectroscopic evidence for such a source in NGC 5253 (Lutz et al. 1996; Calzetti et al. 1999). However if so, this AGN is in a radically different environment from those that usually host AGN.

6. Conclusions

VLA maps at 2 and 1 cm, with the A array, reveal a bright radio source $0.1'' \times 0.04''$, or 2 pc $\times$ 1 pc in size, in the starburst dwarf galaxy NGC 5253. This source is partially optically thick at 2 cm, indicating an emission measure of EM= $\sim 3 \times 10^9$ cm^{-6} pc and an rms electron density of at least 4×10^4 cm^{-3}. The Lyman continuum rate required to excite this source is equivalent to 4000 O7 stars. For a Salpeter IMF with upper and lower mass cutoffs of 40-50 $M_\odot$ and 1 $M_\odot$, respectively, this would imply a cluster of order 10^5 stars within the 2 pc region. This cluster accounts for the entire infrared luminosity of the galaxy as observed by IRAS. We suggest that this source, which we call a radio super nebula, is the very young and gas rich nebular counterpart of super star clusters. Like the Galactic ultra-compact HII regions it resembles, the radio super nebula presents the problem of maintaining such a high density and small volume against its natural tendencies to expand and diffuse.

This work was supported in part by NSF grant AST-9417968 to J.L.T. and by the BSF grant 89-0070 to S.C.B.

REFERENCES

Beck, S. C., Turner, J. L., Ho, P. T. P., Lacy, J. H., & Kelly, D. 1996, ApJ, 457, 610

Calzetti, D., Meurer, G. R., Bohlin, R. C., Garnett, D. R., Kinney, A. L., Leitherer, C., & Storchi-Bergmann, T. 1997, AJ, 114, 1834

Calzetti, D., Conselice, C. J., Gallagher, J. S. III, & Kinney, A. L. 1999, preprint

Campbell, A., Terlevich, R., & Melnick, J. 1986, MNRAS, 223, 811

Crowther, P. A., Beck, S. C., Willis, A. J., Conti, P. S., Morris, P. W., & Sutherland, R. S. 1999, MNRAS, 304, 654

Genzel, R., Becklin, E. E., Wynn-Williams, C. G., Moran, J. M., Reid, M. J., Jaffe, D. T., & Downes, D. 1982, ApJ, 255, 527

Gorjian, V. 1996, AJ, 112, 1886

Habing, H. J., & Israel, F. P. 1979, ARA&A, 17, 345

Kawara, K., Nishida, M., & Phillips, M. M. 1989, ApJ, 337, 320

Kobulnicky, H. A., Skillman, E. D., Roy, J.-R., Walsh, J. R., & Rosa, M. R. 1997, ApJ, 477, 679

Lutz, D. et al. 1996, å, 315, L137

Marlowe, A. T., Heckman, T. M., Wyse, R. F. G., & Schommer, R. 1995, ApJ, 438, 563

Martin, C.L., & Kennicutt, R.C. 1995, ApJ, 447, 171

Massey, P., & Hunter, D. A. 1998, ApJ, 493, 180

Meurer, G. R., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D. R. 1995, AJ, 110, 2665

Mezger, P. G., & Henderson, A. P.1967, ApJ, 147, 471

Rieke,G., Lebofsky, M., & Walker, C. 1988, ApJ, 325

Saha, A., Sandage, A., Labhardt, L., Schwengeler, H., Tammann, G. A., Panagia, N., & Macchetto, F. D. 1995, ApJ, 438, 8

Turner, J. L., & Ho, P. T. P.1994, ApJ, 421, 122

Turner, J. L., Ho, P. T. P., & Beck, S. C. 1998, AJ, 116, 1212

Walsh, J.R., & Roy, J.-R. 1989, MNRAS, 239,297

Wood, D. O. S., & Churchwell, E. 1989, ApJS, 69, 831

This manuscript was prepared with the AAS LaTeX macros v5.0.

Fig. 1.— a) 2 cm VLA map of NGC 5253. The map is contoured at levels of $\pm 2^{n/2}$, n=0,1,2..., times 0.3 mJy/beam (3 σ). The beamsize is $0.33'' \times 0.12''$, p.a. 2°. Peak flux density is 11.8 mJy/beam. The size of the main source, which is located at $13^h39^m55.964^s$, -31°38′24.38″, is $0.1'' \times 0.05''$, or 2 pc x 1 pc. b) 1 cm map. The contour levels are as for a (2.5 σ for this map). The beamsize is $0.22'' \times 0.08''$, p.a. -8°. Peak flux density is 9.1 mJy/beam. The location of the central source is the same as for the 2 cm source; the eastern secondary peak is at $13^h39^m55.98^s$, -31°38′24.4″.

Fig. 2.— Greyscale: HST Hα image of (Calzetti et al. 1997). White patch in the center of the Hα: 1 cm emission. The registration accuracy is limited by the HST image, estimated to be good to $\sim$1″.