THE BIRTH OF A SUPER–STAR CLUSTER: NGC 5253

JEAN L. TURNER
Department of Physics and Astronomy, UCLA, Box 951562, Los Angeles, CA 90095-1562; turner@astro.ucla.edu

AND

SARA C. BECK
Department of Physics and Astronomy and the Wise Observatory, Tel Aviv University, Ramat Aviv, Tel Aviv 69978, Israel; sara@wise.tau.ac.il

Received 2003 December 4; accepted 2004 January 9; published 2004 February 6

ABSTRACT

We present images of the 7 mm free-free emission from the radio “supernebula” in NGC 5253 made with the Very Large Array and the Pie Town link. The images reveal structure in the nebula, which has a ≤1 pc (≤50 mas radius) core requiring the excitation of 1200 O7 stars. The nebula is elongated, with an arc of emission curving to the northeast and to the south. The total ionizing flux within the central 172 (∼20 pc) is 7 × 1052 s−1, corresponding to 7000 O7 stars. We propose that the radio source is coincident with a small very red near-IR cluster and apparently linked to a larger optical source some 10 pc away on the sky. We speculate on the causes of this structure and what it might tell us about the birth of the embedded young super–star cluster.

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

1. INTRODUCTION

NGC 5253 is a peculiar dwarf galaxy containing numerous bright super–star clusters (SSCs; Caldwell & Phillips 1989; Meurer et al. 1995; Gorjian 1996) with ages of ∼2–50 Myr (Calzetti et al. 1997; Tremonti et al. 2001). The current burst of cluster formation may have been induced by accretion of gas from the intergalactic medium via a prominent minor axis dust lane. A bright source less than 2 pc in diameter (Beck et al. 1996; Turner, Ho, & Beck 1998) dominates the radio emission of NGC 5253. The Lyman continuum rate for this single source can explain most if not all of the IRAS luminosity of the galaxy, $L_{\text{IR}} = 1.8 \times 10^8 L_\odot$ at 3.8 Mpc (Turner, Beck, & Ho 2000). Confirmation that the radio source is indeed an H ii region came with the detections of a compact mid-IR source with an IR/radio flux ratio characteristic of H ii regions (Gorjian, Turner, & Beck 2001) and narrow radio and IR recombination lines (Mohan, Ananthamariad, & Goss 2001; Turner et al. 2003). This is a giant ultracompact H ii (UCH ii) region, similar in properties to Galactic UCH ii regions, but with a much larger ionized volume due to the excitation of thousands of O stars (Turner et al. 1998). However, the “supernebula” is different from Galactic H ii regions in that its embedded cluster is so massive. One difference is that the gravitational pull of the cluster may confine the nebular gas to prevent the H ii region from expanding (Turner et al. 2003); as yet, this is the only H ii region known in which this is the case. The star formation in NGC 5253 is also unusually efficient, which is consistent with the formation of a bound cluster (Meier, Turner, & Beck 2002).

We know little about how large bound clusters such as globular clusters form. Young SSCs are found only in other galaxies, where they are difficult to resolve. Enhancements in the high-frequency capabilities of the Very Large Array (VLA) now make it possible to map free-free emission with resolutions of tens of milliarcseconds. At this resolution the great nebula in NGC 5253 can be resolved.

We have mapped NGC 5253 at the highest resolution pos-

1 Visiting Associate, California Institute of Technology.

2 The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.
Fig. 1.—Left: Radio nebula in NGC 5253 at λ = 7 mm with full Pie Town resolution. The uniformly weighted beam is 74 mas × 17 mas, P.A. = 7°, rms noise level is 0.37 mJy beam⁻¹. Contours are ±2σ × 1 mJy beam⁻¹, n = 0, 1, 2 … . The nebula is resolved. The peak intensity of 2.2 mJy beam⁻¹ gives T_{B} = 1100 K, a turnover frequency of 14 GHz, EM = 9 × 10^{14} cm⁻³ pc, and \( n_e = (3–4) \times 10^{4} \text{ cm}^{-3} \). Right: Radio nebula in NGC 5253 with a naturally weighted beam of 93 mas × 34 mas, P.A. = −1° (shown at lower right). Contours are ±2σ × 0.45 mJy beam⁻¹, n = 0, 1, 2, … . The rms noise is 0.11 mJy beam⁻¹ in portions of the image away from the source. Much of the “noise” in this plot is actually undersampled emission. The filamentary arc in the direction of the “optical cluster” to the southeast begins to appear at this resolution.

reflects the full contribution of Pie Town, which provides long mostly east-west baselines. The beam is 74 mas × 17 mas, P.A. = 7°, and the rms noise level is 0.37 mJy beam⁻¹. In this image, the nebula is clearly resolved out. This is important information, since it gives us a brightness temperature. The peak 7 mm intensity is 2.2 mJy beam⁻¹, corresponding to a Rayleigh-Jeans brightness temperature of 1100 ± 200 K. The surrounding T_{B} are ~800–1000 K.

Following Turner et al. (1998) we use the radio spectrum of the H\( \alpha \) region to infer its emission measure, EM = \( \int n_e^2 \, dl \). The peak brightness temperature at 7 mm is 1100 K; thus \( \tau = 0.09 ± 0.02 \), if we assume that T_{B} = 12000 K, similar to the optical nebulae (Walsh & Roy 1987; Kobulnicky et al. 1997). The turnover frequency of the free-free emission, where \( \tau \) equals unity (\( \tau \propto \nu^{-4} \)), is then 14 ± 1 GHz. From the turnover frequency (Mezger & Henderson 1967), we find EM = \( (9 ± 1) \times 10^{14} \text{ cm}^{-3} \text{ pc} \), a value characteristic of UCH \( \alpha \) regions. If we assume that the line-of-sight dimension is equal to its diameter, the density of the bright core is (3–4) \times 10^{3} \text{ cm}^{-3}.

In the right panel of Figure 1, we show a lower resolution image of the supernebula. The beam for this naturally weighted image is 93 mas × 34 mas, P.A. = −1°. With less weighting on the sparse and atmospherically challenged Pie Town baselines, the map has an rms of 0.11 mJy beam⁻¹. While little different in beam size from the previous image, the core of the nebula has become apparent and we begin to pick up traces of filaments to the north and east and a kidney-shaped envelope around the core. The bright core is located at R.A. = 13°39'55.9631, decl. = −31°38’24’.388 (J2000) ± 4 mas and contains 8.5 mJy of flux at 43 GHz. When deconvolved from the beam assuming a Gaussian source distribution, the core has a size of 99 ± 9 mas by 39 ± 4 mas, at P.A. = 6° ± 4°, or 1.8 pc × 0.72 pc (FWHM).

The 7 mm flux for the central 1’2 region is 50 mJy. This corresponds to a Lyman continuum rate of \( N_{\alpha_{Ly}} = (7 ± 1) \times 10^{32} \text{ s}^{-1} \), the equivalent of 7000 O7 stars for the central 1’2 (22 pc) region, 20% (8.5 mJy) of which is confined to the central 1–2 pc bright core, and one-third (15 mJy) to the 5 pc region surrounding the core. The total flux is in agreement with previous fluxes when optical depth is taken into account (Turner et al. 1998, 2000; Meier et al. 2002). From the ionizing flux and a density of \( n_e = 3.5 \times 10^{3} \text{ cm}^{-3} \), we obtain a total gas mass of \( M_{\text{HI}} = 1900 ± 140(n_H/n_e) \, M_{\odot} \) (corrected for He) for the central 1 pc × 2 pc core; and \( M_{\text{HeI}} = 3000(n_H/n_e) \, M_{\odot} \) for the inner 5 pc region. Since the density is lower outside the main core, 3000 \( M_{\odot} \) is a lower limit to \( M_{\text{HI}} \), which scales inversely with \( n_e \).

4. IS THE SUPERNEBULA GRAVITY-BOUND?

One of our goals was to confirm our suggestion that the nebula is gravitationally bound, a finding based on recombination line widths and the size of the radio nebula (Turner et al. 2003). Given our new size and more robust measure of \( N_{\alpha_{Ly}} \), we can refine the calculation of the escape velocity. The core of the supernebula requires the excitation of 1200 O stars. Radio and Brackett recombination line widths are \(~75 \text{ km} \text{s}^{-1} \), FWHM (Mohan et al. 2001; Turner et al. 2003). For a cluster of 1200 O7 stars only and a radius of 0.36 pc, if we assume that the cluster is within the nebula (see § 5), then at the edge of the nebula \( v_{\text{esc}} \) is \(~15 \text{ km} \text{s}^{-1} \); for a Salpeter cluster of stars from O3 to G (\( >100–1 \) \( M_{\odot} \)), a more likely mass function, it is \(~65 \text{ km} \text{s}^{-1} \); and for a Salpeter cluster extending to K–M stars, it is \(~110 \text{ km} \text{s}^{-1} \). In the north-south direction, for a radius of 0.9 pc, these numbers become \(~10, \sim 40, \sim 70 \text{ km} \text{s}^{-1} \), respectively. Whatever the cluster initial mass function may be, the escape velocity is greater than the sound speed. Gravity must play a role in the evolution of the supernebula.

Since the observed line widths are close to \( v_{\text{esc}} \), the gas may actually be in gravitational equilibrium. If so, then the recombination line width of 75 km s⁻¹ gives a mass of \((4–6) \times 10^{3} \, M_{\odot} \). A cluster of this mass is consistent with the observed IR luminosity of \((1–2) \times 10^{5} \, L_{\odot} \) (Gorjian et al. 2001). If so, the nebula can be maintained at its small size indefinitely; in the absence of other confinement, such a dense nebula would have expanded past its present size in less than \( 10^{7} \) yr.

5. INTERACTION OF A YOUNG SSC WITH ITS SURROUNDINGS: FIRST INDICATIONS

Can we learn anything about the young SSC from the structure of its nebula? One obvious question is: where are the stars that excite the supernebula? The excitation requirements are extreme: 1200 O7 stars for the parsec-sized central core, another 2000 O7 stars within the central 5 pc, and a total of 7000 O stars for the inner 20 pc region. These numbers of O stars should be multiplied by \(~100–200 \) for total numbers of stars of all masses. And that is assuming the nebula is density- and a density of \( 3.5 \times 10^{3} \text{ cm}^{-3} \).

In the north-south direction, for a radius of 0.9 pc, these numbers become \(~10, \sim 40, \sim 70 \text{ km} \text{s}^{-1} \), respectively. Whatever the cluster initial mass function may be, the escape velocity is greater than the sound speed. Gravity must play a role in the evolution of the supernebula.

Since the observed line widths are close to \( v_{\text{esc}} \), the gas may actually be in gravitational equilibrium. If so, then the recombination line width of 75 km s⁻¹ gives a mass of \((4–6) \times 10^{3} \, M_{\odot} \). A cluster of this mass is consistent with the observed IR luminosity of \((1–2) \times 10^{5} \, L_{\odot} \) (Gorjian et al. 2001). If so, the nebula can be maintained at its small size indefinitely; in the absence of other confinement, such a dense nebula would have expanded past its present size in less than \( 10^{7} \) yr.

5. INTERACTION OF A YOUNG SSC WITH ITS SURROUNDINGS: FIRST INDICATIONS

Can we learn anything about the young SSC from the structure of its nebula? One obvious question is: where are the stars that excite the supernebula? The excitation requirements are extreme: 1200 O7 stars for the parsec-sized central core, another 2000 O7 stars within the central 5 pc, and a total of 7000 O stars for the inner 20 pc region. These numbers of O stars should be multiplied by \(~100–200 \) for total numbers of stars of all masses. And that is assuming the nebula is density-bounded and no dust absorption. The true number of stars could be larger, although it cannot be too much larger with the observed IR luminosity of \((1–2) \times 10^{5} \, L_{\odot} \) (Gorjian et al. 2001). If so, the nebula can be maintained at its small size indefinitely; in the absence of other confinement, such a dense nebula would have expanded past its present size in less than \( 10^{7} \) yr.
cluster; 7000 O stars can easily produce 2200 $M_\odot$ of gas over their lifetimes.

If the gas is indeed mixed in with the stars, then it could significantly affect the evolution of the young SSC. Intracluster gas provides a source of drag for the orbiting stars and could facilitate stellar collisions and mergers (Bonnell & Bate 2002). The results of these mergers could be extremely massive stars or other massive objects.

If the gas is intermixed with the star cluster, and the ionized gas of the “supernebula” in NGC 5253 is in virial equilibrium, then it is possible that the shape of the nebula reflects the shape of the underlying mass distribution. The elongation of the nebula could indicate that the young SSC is elongated. However, this would not easily explain the larger radio arc, which is beyond gravity’s grasp.

In Figure 2, we overlay our 7 mm radio image on a false-color Hubble Space Telescope (HST)/Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) image of the center of NGC 5253 (data described in Scoville et al. 2000; Alonso-Herrero et al. 2004). The red channel is NICMOS 1.90 $\mu$m continuum, and the blue channel 1.12 $\mu$m; the 7 mm VLA image is in green. There is a diffuse blue “optical source” (source 5 in Calzetti et al. 1997; source 1 in Gorjian 1996) and a bright very red “IR cluster.” The IR cluster appears only in $\lambda \sim 1 \mu$m and is offset $\sim 0.5$ to the northeast of the blue cluster (for spectral energy distributions and ages, see Alonso-Herrero et al. 2004). The absolute pointing accuracy of HST, $\sim 1''$, is inadequate for registration of the IR and radio images. However, the Keck $K$-band (2.2 $\mu$m) image of Turner et al. (2003) shows a single, slightly extended bright source coincident with the compact Brackett line source, and this $K$-band source is also offset to the northwest of the optical source by $\sim 0.5$. It is thus reasonable to identify the “IR cluster” with the $K$-band/Brackett line/radio source. The Brackett lines indicate a visual extinction of $\sim 15$ mag internal to the nebula, which would explain the redness of the IR cluster. While the $K$-band source is extended, and may include emission from nebular dust, the IR cluster at 1.9 $\mu$m is compact, probably an embedded star cluster.

If we adopt the coincidence of the supernebula core and IR cluster, then the faint arc of radio emission curves around in the direction of the optical source, to the southeast. As shown in Figure 2, the optical source appears diffuse compared to other clusters on the NICMOS images. It is only 10 pc in projected distance from the IR cluster. The nature of any association between the optical source and the IR/radio cluster is at this point speculative. The elongation of the supernebula core and the radio arc indicate that the nebula is “aware” of the nearby optical “cluster.” Given the proximity of the two sources in projection, and the gravity-bound gas, could it be that the arc of ionized gas is a reflection of tidal interaction between two massive star clusters, one still embedded, one visible? How will this double cluster evolve? Or is the nebula a blister feature burning its way into the surface of a molecular cloud? In this case, the optical “cluster” may not be a cluster at all, but merely a reflection nebula from a gap opening in the cocoon around the IR cluster, without the ionizing arc tracing the opening of this gap. A reflection nebula would be consistent with the diffuse morphology of the optical source. This possibility suggests another scenario: that the supernebula is cometary. The direction of the ionized arc would then suggest motion of the H II region/cluster to the west and north, which, incidentally, is the approximate direction of the infalling gas clouds of the minor axis dust lane (Meier et al. 2002). Is a cometary supernebula in NGC 5253 the last kinematic remnant of the gas stream from intergalactic space that triggered the birth of this SSC?

6. SUMMARY

We present a 7 mm continuum image of the “supernebula” in NGC 5253 made with the VLA including Pie Town. We have resolved the nebula. Its central core is 1.8 pc $\times$ 0.7 pc in extent (99 mas $\times$ 39 mas) with an rms density of $3.5 \times 10^4$ cm$^{-3}$. It is a giant compact H II region, requiring the excitation of 1200 O7 stars for the parsec-sized core, 3500 stars for the inner 5 pc, and a total of 7000 O7 stars within the central 20 pc. The overall cluster membership implied by this number of O stars is $\sim (1-2) \times 10^4$. 

![Fig. 2.—Left: NICMOS images of NGC 5253. Blue channel is the 1.12 $\mu$m continuum; red channel is the 1.90 $\mu$m continuum. The two central sources are separated by $\sim 0.5$. Right: $Q$-band image of the left panel in green overlaid on the inner $\sim 2''$ of the NICMOS image. We argue in the text that the radio source is coincident with the obscured IR cluster.](image-url)
We confirm the finding of Turner et al. (2003) that the supernebula is gravity-bound, possibly even in virial equilibrium. In the latter case, we obtain a mass of \((4\pm6) \times 10^5 M_\odot\) for the embedded stellar cluster.

We overlay the 7 mm image on a NICMOS near-IR continuum image. There is a heavily reddened IR cluster not evident in optical images. We suggest that this IR cluster is responsible for the radio nebula. A faint radio arc curves in the direction of a bright optical source 10 pc away. The nature of the optical source is unclear; it may be a reflection nebula. The elongation of the core of the supernebula could indicate that the underlying stellar cluster, which is most likely intermixed with the H II region, is itself elongated. Or, the curved shape of the nebula and faint radio arc may reflect interactions of the young cluster with its surroundings, possibly reflecting motion of the newly born cluster within the galaxy.

J. L. T. acknowledges the support of NSF grant AST 03-07950. We thank the VLA scheduling committee for scheduling Q band with the Pie Town link, and an anonymous referee, Mark Claussen, Eric Greisen, and Wes Young for their assistance.

REFERENCES

Alonso-Herrero, A., Takagi, T., Baker, A. J., Rieke, G. H., Rieke, M. J., Imanishi, M., & Scoville, N. Z. 2004, ApJ, submitted
Beck, S. C., Turner, J. L., Ho, P. T. P., Lacy, J. H., & Kelly, D. M. 1996, ApJ, 457, 610
Bonnell, I. A., & Bate, M. R. 2002, MNRAS, 336, 659
Caldwell, N., & Phillips, M. M. 1989, ApJ, 338, 789
Calzetti, D., Meurer, G., Bohlin, R. C., Garnett, D. R., Kinney, A. L., Leitherer, C., & Storchi-Bergmann, T. 1997, AJ, 114, 1834
Dreher, J. W., & Welch, W. J. 1981, ApJ, 245, 857
Gorjian, V. 1996, AJ, 112, 1886
Gorjian, V., Turner, J. L., & Beck, S. C. 2001, ApJ, 554, L29
Kobulnicky, H. A., Skillman, E. D., Roy, J.-R., Walsh, J. R., & Rosa, M. R. 1997, ApJ, 477, 679
Meier, D. S., Turner, J. L., & Beck, S. C. 2002, AJ, 124, 877
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
Mohan, N., Ananthamaria, K. R., & Goss, W. M. 2001, ApJ, 557, 659
Scoville, N. Z., et al. 2000, AJ, 119, 991
Tremonti, C. A., Calzetti, D., Leitherer, C., & Heckman, T. 2001, ApJ, 555, 322
Turner, B. E., & Matthews, H. E. 1984, ApJ, 277, 164
Turner, J. L., Beck, S. C., Crosthwaite, L. P., Larkin, J. E., McLean, I. S., & Meier, D. S. 2003, Nature, 423, 621
Turner, J. L., Beck, S. C., & Ho, P. T. P. 2000, ApJ, 532, L109
Turner, J. L., Ho, P. T. P., & Beck, S. C. 1998, AJ, 116, 1212
Walsh, J. R., & Roy, J.-R. 1987, ApJ, 319, L57
Wood, D. O. S., & Churchwell, E. 1989, ApJ, 340, 265