THE INFRARED AND RADIO MORPHOLOGY OF THE “HOT-SPOT” GALAXY NGC 2903

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ABSTRACT

New maps of the “hot-spot” galaxy NGC 2903 made at the IRTF and VLA show that while the “starburst” model for the activity in the central 0.6 kpc is valid, the star-forming activity is definitely not confined to the hot-spots themselves. We also deduce that the visual appearance of the central regions of NGC 2903 may be at least partially the result of patchy extinction. Comparison of 10-µm and free-free flux densities of this and other galaxies suggests there is an extra component of 10-µm emission from galaxy nuclei above that expected from Lyα heating. It is suggested that this emission may arise from small dust grains that are temporarily heated to high temperatures by visible or UV photons.

Subject headings: galaxies: individual — infrared: sources — interstellar: matter — radio sources: galaxies — stars: formation

I. INTRODUCTION

At visible wavelengths the Sc galaxy NGC 2903 possesses an unusual, complex structure at its center. Photographs taken under average seeing conditions show four to six extended bright peaks spread over a region about 20” in diameter, rather than a single, well-defined nucleus. Following an earlier classification scheme of Morgan (1958), Sérsic (1973) used the term “hot-spot” to describe the nuclear region. Tiftt (1969) and Alloin (1973) found a strong blue component in the emission from the central region of the galaxy that, together with the discovery of emission lines (Alloin 1973), indicated the presence of a population of hot stars. Oka et al. (1974) studied the region with better spatial resolution and concluded that each of the hot-spots in NGC 2903 is an individual giant cluster composed of both early- and late-type stars and H II regions.

The central region of NGC 2903 is a powerful infrared source in the 3–100-µm range, with a bolometric luminosity of 7 × 10^9 L☉ for an assumed distance of 8.6 Mpc (Telesco and Harper 1980). Its size at 10 µm was measured by Rieke (1976) to be 8” (NS) × 4” (EW). Both Telesco and Harper (1980) and Rieke et al. (1980) propose that the infrared emission from NGC 2903 arises from dust heated by a starburst in the nuclear region, as appears to be the case for many spiral galaxies (Scoville et al. 1983). Such a starburst could also, in principle, give rise to the radio continuum emission that is produced in the same general area (van der Hulst, Crane, and Keel 1981) through the production of H II regions or supernova remnants. Other evidence for interesting activity in NGC 2903 includes the presence of noncircular motions (Burbidge, Burbidge, and Prendergast 1960; Simkin 1975) and a possible recent supernova outburst (Laques et al. 1980).

Because of its comparatively high surface brightness and angular size, NGC 2903 provides a good opportunity for examining the morphology of a starburst galaxy in some detail. Of particular interest is whether the hot-spots themselves can be identified as major sources of the infrared luminosity. We have therefore made new maps of the galaxy at a series of visible, infrared, and radio wavelengths. We used V-band, 1 µm, and 2.2 µm to study the distribution of early- and late-type stars; 10 µm to delineate the heated dust; and 2, 6, and 20 cm to investigate the location of thermal and nonthermal radio emission.

II. OBSERVATIONS

The 2.2- and 10-µm maps of NGC 2903 were made on the Infrared Telescope Facility (IRTF) at Mauna Kea Observatory. The 2.2-µm measurements (Fig. 1c), made on 1983 February 8, employed a 2” diameter focal plane diaphragm, a 40” N-S chop and a 6-s integration time at each of 42 points on a 1” × 1” grid. Because of the lower sensitivity at 10 µm, measurements at this wavelength required the use of a 5.7’ focal plane diaphragm (giving a beam of approximately 5” FWHM) to perform 400-s integrations at each of 42 points on a 3” × 3” grid. The 10 µm map (Fig. 1d) is a composite of data taken on 1981 April 5 and 1981 December 16 with a 30” N-S chop plus a few points on 1982 January 2 with a 20” E-W chop. At both 2.2 and 10 µm the absolute positioning was determined by offsetting from a nearby SAO star. The uncertainty in these positions is of the order of 1”. The integrated flux density at 10 µm is 0.9 Jy, in agreement with that measured with a 20” beam by Rieke (1976).

The 1-µm and V-band images (Figs. 1b and 1a) were obtained at the University of Hawaii 2.2-m telescope at Mauna Kea using the Galileo/Institute for Astronomy 500 × 500 three-phase Texas Instruments CCD (Hlavka et al. 1982, 1983). The pixel size was 0”14. Exposure times were 5 minutes for V-band and 10 minutes for the 0.1 µm wide 1-µm filter. The absolute coordinates of the CCD images were determined indireclty; at V-band we fitted the image to the positions of several hot-spots whose locations we had earlier determined both by offsetting the IRTF from a nearby SAO star, and by measurements of the stellar images on a U-band direct Canada-France-Hawaii Telescope (CFHT) photograph (Fig. 2a) kindly lent to us by G. Lelièvre and J-L. Nieto. At 1 µm we simply matched the contours to those of the very similar-looking 2.2-µm image. The flux levels of the CCD images have not been calibrated.

1 Visiting Astronomer, Infrared Telescope Facility, operated by the University of Hawaii under contract with the National Aeronautics and Space Administration.
2 Visiting Astronomer, Very Large Array, an instrument of the National Radio Astronomy Observatory, operated by Associated Universities, Inc., under contract with the National Science Foundation.
The radio continuum emission from NGC 2903 was mapped at the VLA using the “A” array at 20 and 6 cm in 1981 April and the “C” array at 6 and 2 cm in 1981 November. Since the longest spacings available in the “C” array overlap the shortest spacings in the “A” array, we were able to put together a set of 6-cm data covering the same range of spatial frequencies as produced by the “A” array at 20 cm and the “C” array at 2 cm without the need for a third observing run. By this means we produce three maps (Figs. 3a–3c) that were synthesized using identical 2” FWHM circular beams. These three maps are therefore best for studying spectral index variations across the source. We also synthesized two other maps at 6 cm. Figure 3d shows a map made using only “C” array data smoothed to a 5” FWHM circular beam that approximates the resolution of the 10-μm data (Fig. 1d), while the map overlaid on Figure 2a (Fig. 2b), made from “A” array data only, has a beam with FWHM of 1’3 × 1’1 at position angle 66°. Our radio data also include a measurement of the 11-cm flux density made in 1977 November with the Cambridge 3-km telescope. The rather limited structure that could be seen with the 4” (EW) × 11” (NS) beam is compatible with that seen in the 6-cm and 20-cm VLA maps.

III. RESULTS

The V-band CCD contours (Fig. 1a) closely resemble those published by Oka et al. (1974) and Prabhu (1980). The components “a” through “e” are the blue, line-emitting hot-spots as named by Oka et al., while “n” is the distinctly redder component that Prabhu has suggested is the stellar nucleus of the galaxy. The CFHT U-band image of the galaxy (Fig. 2a) shows that there is, in fact, considerably more structure in the central regions than was previously realized. Nearly all of the previously designated hot-spots have been resolved into at least two components, some of which cannot be distinguished from stellar images even under 0’’5 seeing conditions. The photograph also shows direct evidence for the presence of heavy obscuration in the form of a narrow dust lane immediately to the east of component “a.”

The images at 1 and 2.2 μm differ significantly from those at visible and UV wavelengths. The emission is now predominantly from a 15’’ × 10’’ elliptical component extended along the galaxy’s major axis. The main peaks at 2.2 μm are source “n” and a new component to its north that lies between “a” and “b.” These sources have similar intensities, suggesting...
Fig. 2a—$U$-band direct image of the central region of NGC 2903, obtained by G. Lelièvre and J-L. Nieto at the prime focus of the CFHT on Mauna Kea under excellent seeing conditions.
Fig. 2b.—Same as Fig. 2a with the superposition of a 6-cm VLA map made with a 1" x 1" beam.
either that there are two peaks in the distribution of late-type stars in NGC 2903, or that heavy extinction is affecting the appearance of the source at 2.2 μm. Component “c,” the brightest feature at visible wavelengths, is only just distinguishable at 2.2 μm.

Although the spatial resolution of the 10-μm data is insufficient to see structure on the scale of the visible hot-spots, the distribution at 10 μm is clearly very different from that at either near-infrared or visible wavelengths. The source is less extended along the plane than at 2.2 μm, while no sign is seen of component “c,” the brightest visible hot-spot. The peak at 10 μm lies between the two main peaks at 2.2 μm, but the centroids of the emission at the two wavelengths lie close to each other. At 10 μm the source appears to be a little broader in right ascension than estimated by Rieke (1976), but its overall size is in agreement with his multi-aperture photometry.

The radio emission appears to originate from roughly the same 15" diameter region that gives rise to the visible and the infrared emission, although some of the radio flux emanates from east of the visible hot-spots in a region which may be affected by extinction (see Figs. 2b and 3). The agreement between the 10-μm and 6-cm maps (Figs. 1d and 3d) at the 5" scale is reasonably good, but when the 2" maps are compared, very little detailed correspondence can be seen between the bright features at the various wavelengths. The region of brightest radio emission corresponds roughly to components “b” and “d,” but there is no hot-spot coincident with the southern 2 cm radio peak nor with the subsidiary peaks seen at 6 cm and 20 cm. No radio source corresponds to Prabhu’s component “n”; indeed, there is a suggestion in the 20-cm map of a minimum in the radio emission at this position.

The radio emission from the central region of NGC 2903 has a predominantly nonthermal spectrum at all locations. The upper points in Figure 4 show the integrated flux densities of the central 18" × 18" of NGC 2903, which includes essentially all of the emitting regions seen in Figure 3. The radio spectral index of the total emission is ~0.8. The structural differences seen between different wavelengths imply that there are spectral index variations across the source; regions that have a significantly flatter index than the mean are the north and south peaks of the 2-cm map. The spectra of these peaks are

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shown in Figure 4; the spectral indices, although still predominantly nonthermal, are in the range $-0.2$ to $-0.3$, indicating that a free-free component may be present.

IV. DISCUSSION

a) The Morphology of NGC 2903

None of the new data discussed in this paper necessitates any drastic change to the preexisting picture of NGC 2903 as hosting a strong burst of star formation at its center. The most important new result is that the star formation is not simply confined to the "hot-spots" themselves. Star formation appears to be taking place at locations spread over the central 600 pc of NGC 2903, but different parts of this region appear to be relatively more prominent locations of heated dust, ionized gas, synchrotron emission, and blue stars. This kind of agreement in general, but not in detail, is what might be expected if the star formation in NGC 2903 is taking place in a series of small bursts, each of which is currently seen at a different stage of its evolution. Such a situation resembles that in our own galactic center region (Gatley et al. 1978; Odenwald and Fazio 1984). The bursts may be triggering each other in some way, but there are no obvious signs of morphological regularity in NGC 2903, such as the hexagonal symmetry seen in NGC 5248 (Morgan 1958).

The radio and infrared maps indicate that at the present time the most active region of star formation is in the direction of hot-spots "b" and "d." The latter component was the one found by Oka et al. (1974) to have the largest Hβ equivalent width. The conclusion drawn in § III, that part of the radio radiation from the vicinity of "b" and "d" is free-free emission, is in agreement with the detection of the Brα and Brγ lines by Beck, Beckwith, and Gatley (1984). The fluxes they measure, corrected for reddening through an 8" diaphragm centered close to the northern peak of the 2-cm map, correspond to a 2-cm flux of 9 ± 3 mJy if a temperature of 10⁴ K is assumed. This value is fairly close to what we observe at 2 cm. The Brackett-line fluxes imply an ionization rate of $5 \times 10^{52}$ s⁻¹ (Beck, Beckwith, and Gatley 1984), which is about a factor of 50 larger than that implicitly derived for hot-spot "d" by Oka et al. (1974) on the basis of the Hβ flux. This result confirms Beck et al.'s conclusion, based on Brackett-line fluxes, that there must be heavy visual extinction toward at least some of NGC 2903. The existence of this obscuration suggests that the visual appearance of NGC 2903 may be as much the result of patchy foreground extinction as of real variations in stellar population and density. Low extinction toward "c" could explain why it is so strong at visible wavelengths. The presence of patchy extinction in NGC 2903 encourages us to propose a particularly simple model for its nuclear regions in which the stellar density maximum lies in the direction of the radio and 10-μm peaks, behind a band of heavy obscuration that simultaneously causes the 2.2 μm double structure and the large extinction we see toward components "b" and "d."

b) Galactic and Nuclear Star Formation Regions

Since they are seen at such different distances, it is generally hard to compare star-forming regions in the spiral arms of our Galaxy with those in the central regions of starburst galaxies. One of the few parameters that can be compared is the ratio of 10-μm dust emission to 11-cm free-free flux density. Thronson, Campbell, and Harvey (1978) determined the mean value of this ratio to be 10 ± 3 for a large sample of H II region/molecular cloud complexes in our Galaxy. The only extragalactic spiral arm region that has had this ratio measured is NGC 5461 in M101, where the ratio is 14 ± 2 (Blitz et al. 1981).

We have attempted to determine this ratio for NGC 2903 and for the small number of other galaxies for which free-free flux densities can be estimated. We have derived the following results:

NGC 2903: Assuming that the total free-free flux density is no more than 12 mJy (based on Fig. 4) and that the 10-μm flux density for the 20" region is 0.9 Jy, the 10-μm to free-free ratio is at least 70.

M82: An upper limit of 77 mJy for the 11-cm free-free flux density is derived by extrapolating from the 87-GHz measurement of Jura, Hobbs, and Maran (1978) with a spectral index of $-0.1$. A 10-μm flux density of 30 Jy (Rieke et al. 1980) then yields a ratio of $>40$.

IC 342: Data in Becklin et al. (1980) lead to a ratio of 40.

NGC 253: Rieke and Low's (1975) 10-μm flux density of 10.5 Jy, when coupled with Turner and Ho's (1983) estimate of 125 mJy for the 6-cm free-free emission, gives a ratio of 80. In this case the estimate of the free-free emission involves some fairly drastic assumptions about the distribution of the much stronger synchrotron emission, but Turner and Ho's value is in reasonably good agreement with that estimated by Wynn-Williams et al. (1979) on the basis of the Brγ flux density.

NGC 6946: A lower limit of 32 comes from taking Rieke's (1976) flux density of 0.87 Jy with Turner and Ho's (1983) total 2-cm flux density of 23 mJy. A much greater ratio results if Turner and Ho's suggested separation of thermal and nonthermal emission is adopted.

The ratio of 10-μm to free-free emission in starburst nuclei thus appears to be consistently higher than the same ratio in galactic spiral arm/H II region complexes by factors of 3 or more. This effect was noted earlier by Rieke (1976). We have found indications of similar large ratios in two other extragalactic sources, namely the 3-kpc "disk" region of NGC 1068 (Wynn-Williams, Becklin, and Scoville 1985) and the dwarf galaxy II Zw 40 (Wynn-Williams and Becklin 1985). It is most
unlikely that the weakness of the radio emission is due to self-absorption in compact H II regions, since this would require that essentially all of the ionized gas was confined to regions with emission measure greater than 10^9 pc cm^{-6}. Such regions contribute negligibly to the total flux density of star-forming regions in our Galaxy.

These results suggest that in the nuclear regions of galaxies there is a very significant component of extended 10-μm emission above that being produced by Lyα heating in H II regions. This extra component may also explain two other interesting properties of the infrared emission of galaxy nuclei. First, as discussed by Rieke and Lebofsky (1979) and by Frogel, Elias, and Phillips (1982), the 10-20-μm color temperatures of galaxy nuclei are generally higher than those of galactic H II regions. Second, the nuclei of galaxies show much stronger emission in the unidentified infrared bands than do galactic H II regions (Phillips, Aitken, and Roche 1984).

The dust that causes this emission in NGC 2903 must have a 10-80-μm color temperature of at least 125 K in order for its 80-μm flux density to be higher than that observed by Telesco and Harper (1980). Equilibrium dust temperatures this high are very hard to attain except by absorption of trapped Lyα radiation within an ionized region, or by locating the dust within a few tenths of a parsec of an object with the luminosity of at least that of a B star. One possibility is that the emission arises within dense clouds from young luminous objects which, because of some difference between the star-forming process in spiral arms and in nuclei, fail to produce their expected share of H II regions. A dense stellar wind that absorbs the UV radiation close to the stellar surface might produce such an effect. A second possibility is that the 10-μm emission is being produced in the diffuse interstellar medium by a population of small grains that suffer temporary heating to high temperatures by the absorption of a single UV or visible photon. This process has been proposed as the explanation of the 1-5-μm emission from galactic reflection nebulae (Sellgren, Wernert, and Dinerstein 1983). An attractive aspect of this model is the empirical evidence (Sellgren 1984) for a connection between small, hot grains and unidentified infrared emission features like the 8.65- and 11.25-μm lines that Phillips, Aitken, and Roche (1984) see in galaxies similar to NGC 2903.

Temporary heating of small grains to produce 10-μm emission may be a much more widespread phenomenon than hitherto appreciated. We suggest that there is a population of very small grains throughout the interstellar medium with a heat capacity so low that each can be heated temporarily by a single UV photon to a temperature of the order of 300 K. Temporary heating of these grains would be strongest in the vicinity of H II regions, since here the radiation field is likely to be strong at UV (912-3000 Å) wavelengths and the interstellar densities are likely to be large. This type of grain heating differs from conventional equilibrium heating, however, in that the grain temperature is independent of distance to the source of radiation. Under most circumstances the 10-μm radiation from these grains will be very hard to see using ground-based techniques, since it will be of very low surface brightness and will be too extended to be visible with a “chopping” infrared photometer. Thronson and Price (1982), however, in their analysis of Air Force Geophysical Laboratory rocket observations, noted the existence of a region of extended low-brightness 10-μm emission near the galactic H II regions W3/W4/W5; a search of Infrared Astronomical Satellite (IRAS) data for similar effects in other galactic regions might be profitable. As far as ground-based observations are concerned, however, emission from very small, hot grains will be easier to detect in external galaxies than in our own. This is because a starburst region of a galaxy such as NGC 2903 provides a much more potent combination of a strong UV radiation field and a high dust column density than can be found in the spiral arms of our Galaxy.

V. CONCLUSIONS

Mapping of the infrared and radio emission from the central 20' of NGC 2903 has shown that:

1. The radio emission is predominantly nonthermal, but in some regions the free-free emission contributes substantially at 2 cm.
2. The bursts of star formation giving rise to the infrared emission from NGC 2903 are not confined to its visible hotspots.
3. The visual appearance of the hot-spot region may be due as much to extinction as to variations in stellar population and density.
4. In NGC 2903 and in other spiral galaxies, the ratio of 10-μm to free-free emission is greater than for spiral-arm H II region/molecular cloud complexes. We suggest that this emission arises from small dust grains that are temporarily heated to high temperatures by visible or UV photons.

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