INFRARED HOT SPOTS IN THE NUCLEUS OF NGC 253

DUNCAN A. FORBES

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, England

MARTIN J. WARD

Astrophysics, Nuclear Physics Laboratory, Keble Road, Oxford, OX1 3RH, England

AND

D. L. DEPOY

Astronomy Department, Ohio State University, 174 West 18th Avenue, Columbia, OH 43210-1106; and Cerro Tololo Inter-American Observatory, La Serena, Chile Received 1991 February 25; accepted 1991 August 5

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ABSTRACT

Near-infrared observations of the starburst galaxy NGC 253 using a large-format array and high spatial sampling show four knots of enhanced emission (hot spots) in the nuclear region. We find that each hot spot may correspond spatially to a compact radio knot. We discuss several possible origins of these hot spots and suggest observational tests of the possibilities.

Subject headings: galaxies: individual (NGC 253) - galaxies: nuclei - infrared: sources - stars: supernovae

1. INTRODUCTION

NGC 253 is a well-studied, nearby example of a starburst/ LINER galaxy (see McCarthy, Heckman, & van Breugel 1987). Evidence for vigorous star formation in the nucleus of NGC 253 includes large far-infrared luminosity and CO line emission (Scoville et al. 1985), X-ray emission (Fabbiano & Trinchieri 1984), compact radio sources (Antonucci & Ulvestad 1988), strong narrow-line emission (Moorwood & Oliva 1988; Wright & Joseph 1989), and spectral signatures indicating high-velocity outflows (McCarthy et al. 1987). The high rate of gas consumption and evidence for massive stars in NGC 253 suggest a prodigious star formation rate and a correspondingly high supernova rate. Radio observations using the VLA have detected families of compact radio sources, which are believed to be young supernova remnants (SNRs). The supernova rate in the nucleus estimated from these observations is about one every 3 yr (Antonucci & Ulvestad 1988). However, there is no direct optical confirmation of these supernovae (SNs), presumably due to the enormous dust obscuration present (Rieke & Low 1975; Waller, Kleinmann, & Ricker 1988). We have obtained images of NGC 253 in the infrared, where the effects of extinction are lessened, at both low and high spatial resolution. The images allow accurate astrometry and are well suited to a search for compact infrared hot spots, which may be associated with the radio sources and supernova events.

2. OBSERVATIONS

We have obtained a series of infrared (IR) images of NGC 253 at the Cerro Tololo Inter-American Observatory (CTIO). The observations are summarized in Table 1. Standard procedures for data reduction were used (i.e., dark and sky subtraction and flat-fielding by a median sum of all sky frames). Images taken in 1990 were obtained with a camera that uses a 256×256 pixel PtSi array provided to NOAO by the Hughes Aircraft Corporation installed in a standard CTIO CCD dewar. Images taken on 1989 September 17, with a 62×58 pixel InSb array, were calibrated using flux standard stars from

Elias et al. (1982), which were observed several times throughout the night.

3. RESULTS

Figure 1 (Plate L2) is a large field-of-view (~10') image of NGC 253 at H (1.65 μ m). This image is perhaps the largest single IR image of a starburst galaxy currently available (previously IR images of nearby galaxies required a mosaic of images due to the small size of the detector). The insert in Figure 1 shows an H image of the nucleus obtained at extremely high spatial resolution (0".05 pixel⁻¹). This image was taken in good seeing conditions (~0".7 FWHM) and

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INFRARED OBSERVATIONS

Parameter	Value				
1989 September 17					
Telescope Array Pixel scale Seeing Filters	CTIO ^a 4 m SBRC 62 \times 58 InSb 0"32 pixel \sim 1"8 J, H, K, and L				
1990 July 31					
Telescope Array Pixel scale Seeing Filter	CTIO 4 m Hughes 256 \times 256 PtSi 0".05 pixel \sim 0".7 H				
1990 August 31					
Telescope Array Pixel scale Filter	CTIO Schmidt Hughes 256×256 PtSi 2".91 pixel ⁻¹ H				

^a Cerro Tololo Inter-American Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.



FIG. 1.—Infrared image of the nearby starburst galaxy NGC 253, using a 256 \times 256 pixel array with an *H* (1.65 μ m) filter, taken on the Schmidt telescope at Cerro Tololo Inter-American Observatory. The insert shows the nucleus at $\sim 60 \times$ higher resolution, revealing several infrared "hot spots."

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FIG. 2.—Logarithmic contour maps of NGC 253 in J (1.25 μ m), H (1.65 μ m), K (2.2 μ m), and L (3.5 μ m) at 0".32 pixel ⁻¹ (left to right). Contour steps are ~0.1 in the log. Each tick mark corresponds to 5 pixels (1".6). Only hot spot A (location ~ 30, 33) is clearly resolvable from the nuclear light. North is up, and east is left.

reveals several regions of enhanced emission (hot spots) as well as the central nucleus. A series of contour maps at J (1.25 μ m), H, K (2.20 μ m), and L (3.5 μ m) are shown in Figure 2.

Using the large field-of-view image we measured the position of the nucleus relative to stars in the frame with known positions. We find the position of the nucleus to be $\alpha = 0^{h}45^{\bar{m}}5^{s}9$, $\delta = -25^{\circ}33'40''.1$ (1950), with a positional uncertainty of $\pm 1''.2$ given by the rms residuals from seven stars. This is consistent with previous measurements of the nuclear position at K (e.g., Becklin, Fomalont, & Neugebauer 1982). Furthermore, this position is consistent with the strongest 6 cm source of Antonucci & Ulvestad (1988), so we will assume the IR nucleus is coincident with the 6 cm radio nucleus. A contour map of the high spatial resolution nuclear image is shown in Figure 3 along with the locations of strong (>1 mJy) 6 cm sources. The centroid positions of the hot spots and radio sources are given in Table 2A. All four identified hot spots are within 1" of radio sources, with an average offset of 0".72 and a general positional pattern similar to the distribution of radio sources. We note that the intensity of hot spot D is less than that of A even

though D is the stronger 6 cm source and that another strong radio source located at $\alpha = 0^{h}45^{m}5.625$, $\delta = -25^{\circ}33'41''.24$ (1950) has no IR counterpart. This may be explained by the higher extinction to the SW of the nucleus (Rieke & Low, 1975; Waller et al. 1988) obscuring the IR emission.

The high-resolution image shows that hot spot A has a FWHM, from an azimuthally averaged profile, of ~1".6. After correcting for the seeing disk (assuming $FWHM_{cor}^2 = FWHM_{obs}^2 - FWHM_{psf}^2$) the angular size of hot spot A is ~1".4 or 17 pc (assuming a distance of 2.5 Mpc).

Table 2B gives estimates for the J, H, and K magnitudes from hot spot A taken from the low-resolution (0".32 pixel⁻¹) images. A 2" aperture was centered on the position of hot spot A and the surrounding galaxy emission subtracted to determine the brightness of the enhanced emission. Because the galaxy's surface brightness at this position is substantial, the error in determining the flux from the hot spot is large ($\approx \pm 0.5$ mag). The fluxes from the other hot spots were impossible to determine due to their close proximity to the very bright nucleus.



FIG. 3.—Logarithmic contour map of the high-resolution $(0.05 \text{ pixel}^{-1}) H$ image of the nucleus of NGC 253 (see also insert in Fig. 1). Contour steps are 0.1 in the log. Several hot spots are seen along with the central nucleus. Also shown is the location of the compact 6 cm sources from Antonucci & Ulvestad (1988) nearest to these hot spots (see text for details). The ellipse represents the size of the synthesized radio beam (0.55 × 0.31).

TABLE 2	
INFRARED HOT SPO	DTS

A.							
IR Po	osition ^a	Radio H	Position ^b				
6 * 03	37″.16	5 * 998	36″.96				
5.95	38.81	5.598	37.81				
5.85	37.89	5.906	37.45				
5.69	40.00	5.727	40.01				
В							
Filter		Spot A ^c mJy ⁻¹)					
)	15.	3/1.2					
ı)	14.	5/1.6					
ı)	13.	3/2.9					
)	11.	5/7.3					
	A IR Pc 6*03 5.95 5.85 5.69 B er)	A. IR Position ^a 6*03 37".16 5.95 38.81 5.85 37.89 5.69 40.00 B. Hot er (mag) 15.) 13.) 11.	A. IR Position ^a Radio F 6*03 37"16 5*998 5.95 38.81 5.598 5.85 37.89 5.906 5.69 40.00 5.727 B. Hot Spot A ^c (mag mJy ⁻¹)) 15.3/1.2) 13.3/2.9) 11.5/7.3				

^a Assuming the *H*-band nucleus is located at $\alpha = 0^{h}45^{m}5^{s}.794$, $\delta = -25^{\circ}33'28''.99$ (1950) i.e., coincident with the radio nucleus (see text for details).

^b Location of corresponding compact radio source (Antonucci & Ulvestad 1988); positional uncertainties are ± 0 ?02.

^c Flux densities from a 2" aperture centered on the *H*-band hot spot position after subtraction of the underlying galaxy light. Errors are approximately ± 0.5 mag and are discussed in the text.

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4. NATURE OF THE IR HOT SPOTS

The high-resolution near-infrared images of the nuclear regions of NGC 253 show four hot spots that are spatially near compact radio knots. The nature of the radio knots is not precisely understood, since low flux levels make definitive identification of individual compact sources difficult. However, in M82, which in many ways resembles NGC 253, the brightest compact radio source is located some distance from the dynamical center and reveals many characteristics of a young SNR. In particular, variability over several years rules out an H 11 region origin (Kronberg, Biermann, & Schwab 1985). The brightness temperatures of the central nucleus in NGC 253 excludes an H II region as the dominant source of the radio emission. The spectral index and brightness temperature for some of the stronger radio sources in NGC 253 have been measured by Turner & Ho (1985) and found to be consistent with SNRs. We can estimate the total minimum energy present from the compact radio sources by assuming an equipartition of particle and magnetic field energies (e.g., Moffet 1975). Given that these sources are unresolved we take their sizes to be equal to the restoring beam $(0.55 \times 0.31 \text{ arcsec}^2)$ and assume a spectral index of 0.85 (S $\propto v^{-\alpha}$) between 100 MHz and 15 GHz, a filling factor of unity, and that the particle energy equals the electron energy. We find that the total minimum energy for the radio sources varies between $\sim 10^{49}$ ergs for the weakest sources and 1.3×10^{50} ergs for the nucleus. These values are consistent with the energy output from SNRs. It is therefore natural to assume that the compact radio features seen in NGC 253 are associated with radio supernovae or young SNRs.

Several possibilities exist for the origin of the enhanced IR emission. These include giant H II regions, clusters of red giants or supergiants, supernovae or supernova remnants, and local minima in the extinction (holes). The general similarities between the distributions of the IR hot spots and the radio knots suggests, however, that whatever the emission mechanism, some association with supernovae or supernova remnants is plausible. For example, if the IR hot spots are simply holes in the extinction, then the holes may be caused by the destruction or displacement of dust by the supernova remnants causing the radio sources.

4.1. Giant H II Regions

Optical hot spots have been identified in the nuclear regions of a number of late-type spiral galaxies (Sersic & Pastoriza 1965). Subsequent spectroscopic observations revealed that in most cases these hot spots were H II regions (Osmer, Smith, & Weedman 1974). The IR hot spots seen in the nucleus of NGC 253 may represent similar dusty H II regions. The IR colors of hot spot A are consistent with heavily reddened ($A_V \sim 11$ mag) O stars combined with a small contribution from hot dust (Campbell & Terlevich 1984). Type II SNs are often located in or near H II regions; their remnants would be consistent with the general spatial agreement between the radio and IR.

4.2. Red Supergiants

A variety of evidence suggests the presence of a large number of red supergiants (RSGs) in the nuclear region of NGC 253 (Rieke et al. 1980), and a RSG is the most likely progenitor of a supernova in a starburst nucleus. An estimate of the IR flux from hot spot A after subtraction of the mean background is given in Table 2B. Although rather inaccurate (± 0.5 mag), the flux densities derived are similar to those estimated for the IR hot spots seen in M82 (Pipher et al. 1987), and the colors are consistent with a cluster of RSGs (Campbell & Terlevich 1984). If we assume an absolute K magnitude for a RSG of -11.5, then only four such stars are required to generate the enhanced K emission from hot spot A.

4.3. Supernovae and Supernova Remnants

The family of compact radio sources in NGC 253 were first seen in 1983 October (Turner & Ho 1985). Therefore, these sources are sufficiently evolved that any IR emission observed would be due to warm dust in the shell associated with a SNR (we can exclude nonthermal processes from the SNR as the source of the IR emission since the observed enhanced emission at K is $\sim 10^3$ greater than that expected from an extrapolation, assuming $\alpha = 0.85$, of the nonthermal emission). Theoretical studies of the evolution of a SNR in a dense environment (Wheeler, Mazurek, & Sivaramakrishnan 1980; Shull 1980; Dwek 1983) suggest that the optical and ultraviolet flux will be absorbed by preexisting dust and reradiated in the IR. The exact nature of the IR source requires modeling several parameters including the density of circumstellar material, but the 2 μ m flux from hot spot A is consistent with the general expectations of the models (see Fig. 4 in Wheeler et al. and the prediction for 300 K Fe grains by Shull). Furthermore, the IR colors of hot spot A (from Table 2B: J-H = 0.82 and H-K = 1.17) are consistent with the observations of known Type II SNs some years after the explosion (Dwek 1983).

Traditionally, variability has been used to confirm the existence of a supernova. Additional J, H, and K images were obtained at Kitt Peak National Observatory using a 62×58 pixel InSb array in 1990 November. Unfortunately, poor seeing (2''-3'') in these images makes a determination of the flux from the hot spots very unreliable. We can therefore only place a weak upper limit of less than 30% variability in the variability in the hotspots after one year. Terlevich (1990) has argued that the decline in the IR luminosity from an expanding shell is not rapid, however, so variability may be difficult to detect even under more favorable conditions.

5. CONCLUSIONS AND FUTURE WORK

With the available data, we have not been able to positively identify the nature of the IR hot spots in NGC 253. However, each hot spot may be spatially associated with a compact radio knot, suggesting that the emission mechanism could be associated with supernovae or supernova remnants. Further photometric monitoring may indicate a direct connection between the hot spots and SNRs, but high spatial resolution spectroscopic imaging may be more informative. For example, strong CO absorption lines in the hot spots will indicate the presence of supergiants, whereas strong [Fe II] (1.26 μ m and 1.64 μ m) and weak Br γ (2.17 μ m) will confirm that a SNR, and not an H II region, is the dominant source of the IR emission (Moorwood & Oliva 1988).

Infrared images should be obtained of other starburst galaxies where high supernova rates are expected (see also van Buren & Norman 1989). These sources with numbers of compact radio sources may be of particular interest. Finally, we note that distinct peaks in the IR emission are often interpreted as evidence for double nuclei and thus a merger; caution should be exercised as this is not always the case. L66

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