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VLA OBSERVATIONS OF MASSIVE STAR FORMATION IN SPIRAL NUCLEI

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ABSTRACT

We utilize both the spectral and spatial information in high-resolution radio continuum maps to decouple thermal emission due to H II regions from the extended, strong synchrotron emission found in galactic cores. A first-order analysis, assuming constant spectral indices across the maps, yields thermal fluxes to within a factor of 2. We thus confirm the presence of large numbers of H II regions and young stars in the nuclear regions of three nearby spiral galaxies.

Subject headings: galaxies: nuclei — nebulae: H II regions — radio sources: general — stars: formation

I. INTRODUCTION

Recent mid-infrared and far-infrared observations of spiral galaxies have revealed prodigious nuclear luminosities, of magnitudes comparable to their bolometric luminosities (Rieke and Lebofsky 1978; Telesco and Harper 1980). The extremely low mass-to-luminosity ratios derived from the infrared emission and the thermal nature of the infrared spectrum suggest that the radiation is emitted by dust grains heated by ultraviolet photons from large numbers of young stars. Optical emission lines also suggest the occurrence of active star formation in spiral nuclei (Stauffer 1981; Heckman 1980; Keel 1982), although the high extinctions implied by the infrared measurements indicate that the optical emission must frequently originate in regions exterior to the nucleus. Radio observations are impervious to such extinction. Moreover, the thermal bremsstrahlung component of radio emission directly measures the number of ionizing photons, thereby setting limits on the number of young stars. Strong nonthermal synchrotron emission, however, dominates the thermal bremsstrahlung emission at centimeter wavelengths, for single-dish or low dynamic range studies. With the resolving power of the Very Large Array (VLA), it is possible to separate the dominant and smooth nonthermal emission from the clumpy thermal emission from H II regions by studying the spatial distribution of the spectral index with high angular resolution. In this *Letter* we report the application of this technique in the detection of thermal radio emission and confirm the presence of H II regions in the cores of nearby spiral galaxies.

II. OBSERVATIONS

Our sample consists of the three nearby spiral galaxies listed in Table 1. The galaxies were chosen on the basis of proximity, morphological similarity, and infrared brightness suggestive of thermal activity. For optimal resolution and sensitivity, we observed in the B array at 6 cm, and the C array at 2 cm, yielding matching beams of approximately 1″ full width half-maximum for the spectral analysis. We chose 6 cm for maximum sensitivity and 2 cm to enhance the thermal emission component relative to the nonthermal. Identical angular resolution at the two wavelengths ensures sensitivity to the same spatial structures.

The observations were made with the VLA of the National Radio Astronomy Observatory,[3] at 6 cm on 1981 July 11, and at 2 cm on 1981 November 13. The flux calibrator was 3C 286, with assumed fluxes of 7.50 Jy at 6 cm and 3.44 Jy at 2 cm. The phase calibrators for the individual galaxies are listed in Table 1. The resulting maps were CLEANed (Clark 1980) and self-calibrated (Schwab 1980) whenever the sources were sufficiently strong. Approximately 2 hours of observing time were spent on each galaxy. The achieved rms noise figures are 0.07 mJy per beam at 6 cm and 0.4 mJy per beam at 2 cm. The sensitivity for NGC 253 at 6 cm is 0.15 mJy per beam, determined by the 500:1 dynamic range imposed by the bright compact source. Our maps of NGC 253 and IC 342 are in good general agreement with those of Condon *et al.* (1982) despite the different angular resolutions and wavelengths observed.

III. RESULTS

The 6 and 2 cm maps of the galaxy cores are presented in Figure 1. Spectral index maps, obtained from the 6 and 2 cm maps by the following transformation,

$$\alpha = -\log(S_6/S_2)/\log(\nu_2/\nu_6),$$

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TABLE 1

SPIRAL GALAXY SAMPLE

GALAXY	POSITION[a]		DISTANCE (Mpc)	CALIBRATORS		TOTAL FLUX		THERMAL FLUX		LOG N_i (s^{-1})	NUMBER OF OB STARS[b] ($\times 10^4$)
	R. A.	Decl.		6 cm	2 cm	6 cm	2 cm	6 cm	2 cm		
NGC 253......	$00^h45^m05^s.8$	$-25°33'39''.8$	2.5	0202−172	0135−247	1400	640	125	110	52.88	4.7
IC 342	$03^h41^m57^s.3$	$67°56'29''$	3.5	0212+735	0224+671	82	38	42	38	52.70	2.7
NGC 6946	$20^h33^m49^s.2$	$59°58'49''.5$	7.1	2021+614	2021+614	39	23	4	3.6	52.29	7.9

[a] Coordinates refer to central compact sources likely to be the nucleus, except for IC 342 which does not exhibit a dominant compact component.

[b] Number of OB stars with a Miller-Scalo 1979 initial mass function and a maximum spectral type of O4.

are presented in Figure 2. Each map was clipped at the 6 σ level before computation. The clipping tends to eliminate extended nonthermal emission, which is weak at 2 cm, from the spectral index maps. The error in α is determined by the noise in the 2 cm map and is largest at the lowest flux levels. A 1 σ error at 2 cm will lead to an error of 0.15 in α at the clipping level. The high spatial resolution of the maps successfully separates regions of flat or positive spectral index, indicative of thermal bremsstrahlung from young stars, and negative spectral index areas of smooth synchrotron emission. The high brightness source at the center of NGC 253 appears to have a flatter spectrum and may be an optically thick synchrotron source, as may be the central source in NGC 9646 (van der Hulst, Crane, and Keel 1981; Kellerman and Pauliny-Toth 1981); noncentral flat spectrum sources of low brightness are likely to be H II regions.

At any point in our maps, the thermal and nonthermal fluxes can be estimated from

$$S_{6_t} = \left[S_2 - S_6(\nu_2/\nu_6)^{\alpha_{\rm nt}}\right]\left[(\nu_2/\nu_6)^{\alpha_t} - (\nu_2/\nu_6)^{\alpha_{\rm nt}}\right]^{-1},$$

$$S_{6_{\rm nt}} = S_6 - S_{6_t},$$

where the subscripts t and nt denote thermal and nonthermal contributions. Since the measured α reflects both thermal and nonthermal contributions and not α_t and $\alpha_{\rm nt}$ directly, a first-order estimate of the total thermal flux density can be obtained by assuming constant spectral indices for the thermal and nonthermal components across the map. This procedure makes use of the observed extended nature of the nonthermal emission in the calculation of its contribution at any particular map position. If we further assume $\alpha_t = -0.1$ for the thermal component and fit the nonthermal spectral index, we obtain $\alpha_{\rm nt} = -0.6$ for IC 342 and NGC 6946, and -1.0 for NGC 253. The criterion for the fit is the minimization of noise fluctuations in the map. The noise level in the component maps is 0.5 mJy per beam, which is close to the noise level of the 2 cm map. The derived thermal fluxes are presented in Table 1. A more complete analysis involves the relaxation of the assumptions on α, which we defer to a later paper.

From the thermal fluxes and the assumptions of spherical symmetry and optically thin emission, we estimate the total number of ultraviolet photons,

$$N_i = 9.77 \times 10^{49}[D\,(\text{Mpc})]^2[S_6\,(\text{mJy})].$$

This is likely to be an underestimate if there are optically thick regions. The number of early-type stars required to provide the ionizing photons is then estimated from the stellar data of Panagia (1973) and from a Miller and Scalo (1979) initial mass function. The number of stars thus derived, which includes only stars of spectral type B3 and earlier, is presented in Table 1.

Although high-resolution radio continuum measurements are an inherently accurate method of determining the number of massive young stars, the thermal fluxes derived are uncertain because of our assumption of constant α across the maps. The thermal flux error is a function of the spectral index assumed and the variation of spectral index across the maps, but it is most strongly a function of the nonthermal-to-thermal flux ratio. Therefore, in IC 342 and NGC 6946, where the thermal regions are dominated by thermal emission, we estimate the error by the noise level of the component maps, which is a measure of the error in the fitted $\alpha_{\rm nt}$. We thereby derive uncertainties of 1.2 for NGC 253 and IC 342, and 2.5 for NGC 6946. In NGC 253, the strength of the synchrotron disk emission renders our thermal flux estimates more sensitive to the spectral index variations. Assuming an axisymmetric distribution for the extended component, and using measured spectral index variations, we derive uncertainties of 1.6 for the inner and 1.2 for the outer thermal knot. We therefore estimate that a factor of 2 is a conservative estimate of the uncertainty in total thermal flux density for NGC 253. We anticipate that these uncertainties can be improved with more sophisticated models.

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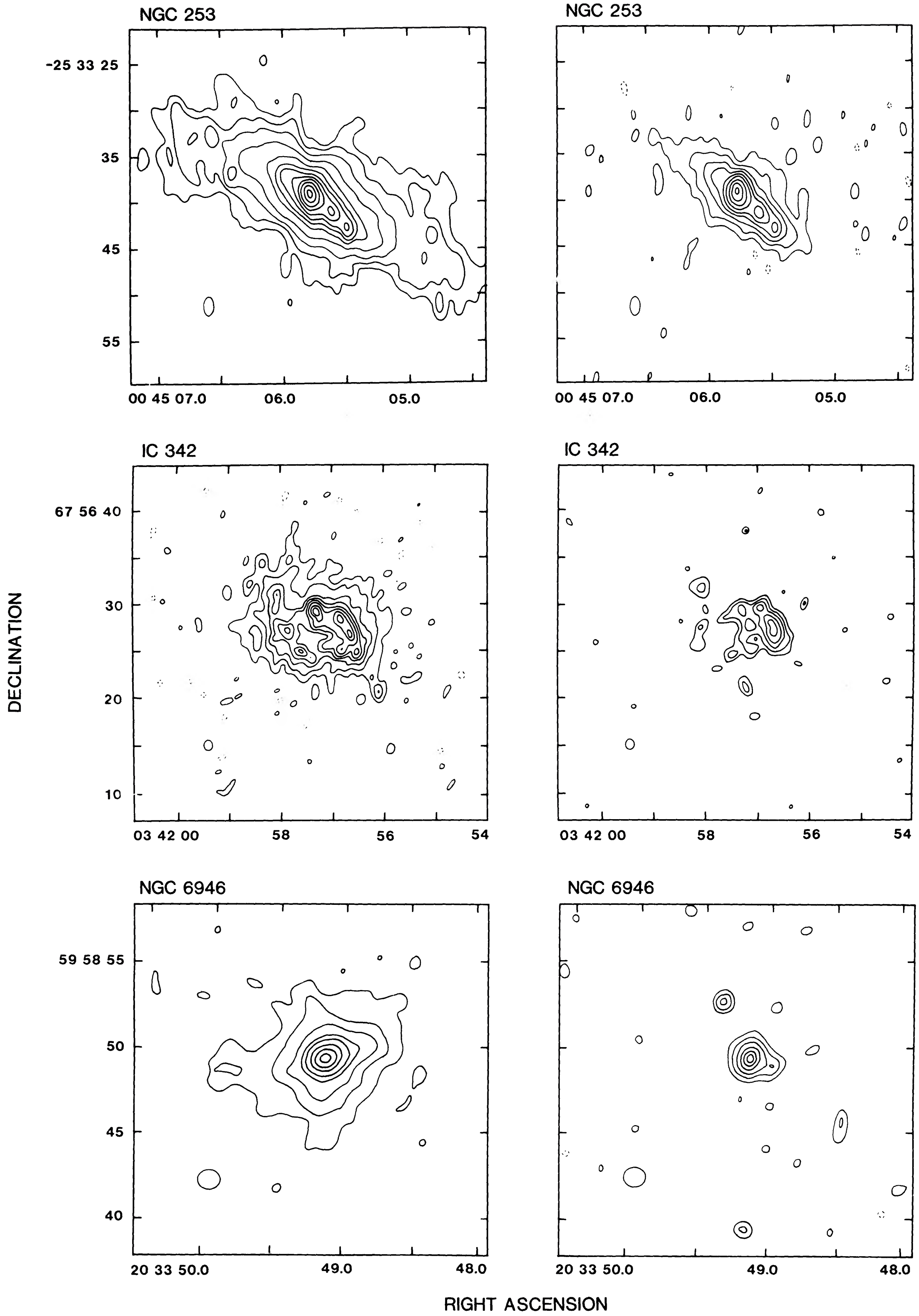

FIG. 1.—The 6 and 2 cm maps of (*upper*) NGC 253, at flux densities of −0.62, 0.62, 1.0, 2.1, 4.2, 10, 20, 30, 48, 70, 104, 145, and 188 mJy per beam area (6 cm) and −1.2, 1.2, 3, 12, 24, 36, 58, 88, and 131 mJy per beam area (2 cm); (*middle*) IC 342, at flux densities of −0.14, 0.14, 0.28, 0.56, 0.84, 1.1, 1.4, 2.0, and 2.5 mJy per beam area (6 cm) and −0.9, 0.9, 1.2, 1.8, 2.1, and 2.7 mJy per beam area (2 cm); and (*lower*) NGC 6946 at flux densities of −0.15, 0.15, 0.38, 0.75, 1.5, 2.3, 3.8, 5.3, and 6.8 mJy per beam area (6 cm) and −0.88, 0.88, 1.3, 1.8, 2.6, 3.5, and 4.0 mJy per beam area (2 cm). Beams are depicted in the lower left corner of each map.

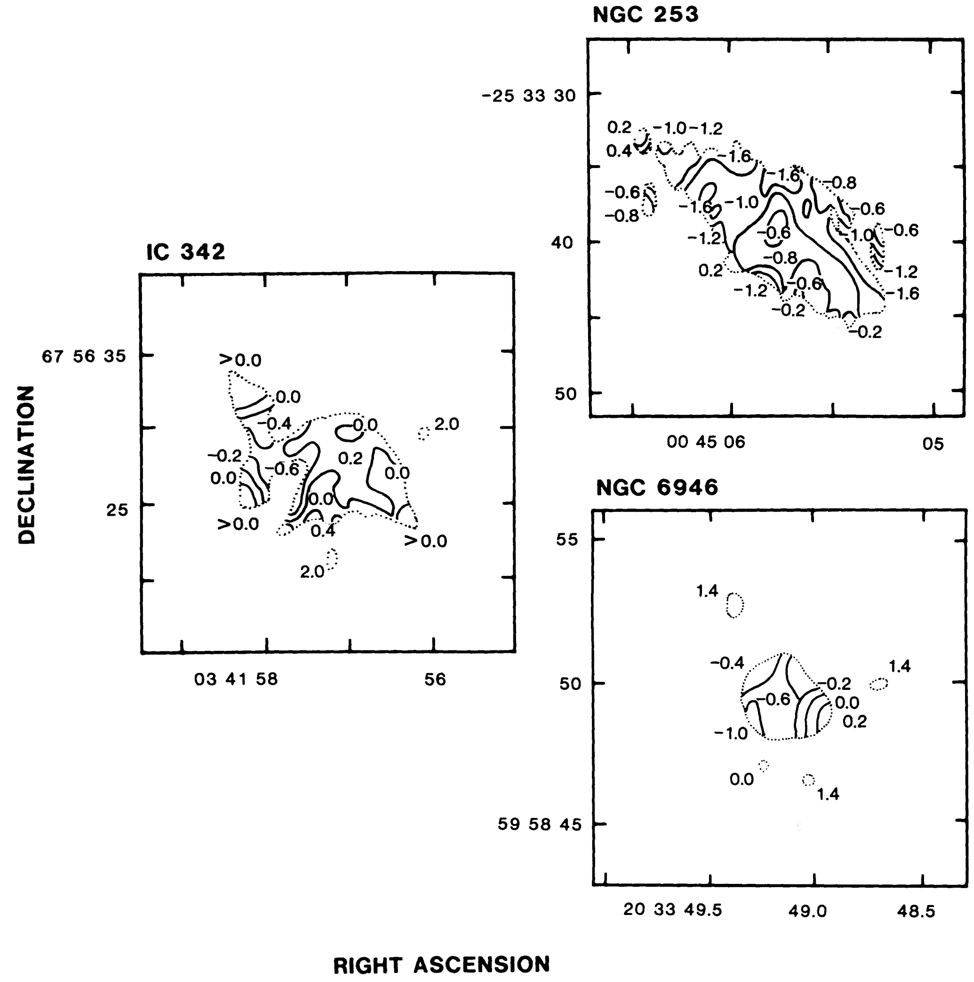

FIG. 2.—Spectral index maps as defined in the text. Negative spectral index represents areas of nonthermal emission, and flat or positive spectral index represents thermal emission from H II regions. The maps are contoured at intervals of 0.2 unless otherwise noted; the numbers refer to the mean spectral index of the bin.

IV. DISCUSSION

Extragalactic radio H II regions have been detected in galactic disks (Israel 1980, and references therein). Strong nonthermal emission from galactic cores makes detection more difficult in the nuclear region, with the magnitudes of the fluxes and typical size scales expected for extragalactic H II regions placing severe constraints on possible observational techniques. The flux densities of H II regions at Mpc distances are typically a few mJy, which can easily be detected in the radio continuum. However, given the ubiquity of high-brightness nonthermal sources in galactic nuclei (van der Hulst, Crane, and Keel 1981), a more important consideration is often dynamic range: normal Galactic H II regions will be rendered undetectable by a 1 Jy nuclear source at a dynamic range of less than 500:1. Under these circumstances, a fairly complete VLA map is necessary. When dynamic range is not a problem, a 2 hour VLA map will detect H II regions of an emission measure of 8×10^5 cm^{-6} pc, corresponding to a moderately dense Galactic H II region (Habing and Israel 1979). This sensitivity effectively limits detection to galaxies within 10 Mpc.

Our angular resolution is constrained by the competing demands of sensitivity versus exclusion of the maximum amount of nonthermal emission from the beam, for which the optimal resolution is on the order of the size of the H II region. For our galaxy sample and the VLA B/C configurations, the achieved resolution was 1″, which corresponds to a linear resolution of 10–30 pc.

Our results demonstrate that it is possible to separate the thermal and nonthermal components of the nuclear emission. We obtain a value for the number of young stars with relatively small and well-understood errors. It

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is clear from inspection of the maps that, despite the enormous variations in the strength of nonthermal nuclear emission and in the nuclear morphology within the Sc/Scd class, the numbers of young stars in the nuclear regions are comparable. This trend needs to be studied with a larger sample. We shall briefly note some of the similarities and differences within the galaxy sample.

The nonthermal emission of NGC 253 consists of an unresolved (< 12 pc) source of 175 mJy flux density and an extended "disk" emission of 1 Jy distributed over 30″ (360 pc). The thermal component, consisting largely of two knots southwest of the nucleus, is strikingly asymmetric, but this is not surprising in view of the asymmetries noted in the near-infrared (Rieke and Low 1975), in [Ne II] (Beck, Beckwith, and Gatley 1982), and in the large visual extinction observed to the southwest (Rieke and Low 1975; Keel 1982). The extended nonthermal disk emission, however, is quite symmetric about the central source. This may indicate that the disk emission is related to the compact source rather than supernovae associated with the star-forming regions.

Compared with NGC 253, the nonthermal nuclear emission in IC 342 is weak while the thermal emission is similar. There is no source which can be unambiguously identified as a compact synchrotron source on the basis of symmetry or brightness temperature. The most likely candidate for such a source, on the basis of its central ($\alpha = 3^{\rm h}41^{\rm m}57\overset{\rm s}{.}3$, $\delta = 67°56'29''$) position and high percentage of synchrotron emission, has a flux density of 2.3 mJy, nearly two orders of magnitude fainter than NGC 253, or approximately twice as bright as the Galactic source Sgr A with equivalent angular resolution (Haynes, Caswell, and Simons 1978). The total nonthermal disk emission at 6 cm is 40 mJy and is intimately associated with the star-forming regions. The individual thermal sources, of fluxes consistent with 10^2–10^3 OB stars, are distributed in a spiral out from the compact nuclear source to a distance of 200 pc, in the same sense as the spiral arms. Our calculated population is in agreement with the estimate of 10^3–10^5 OB stars made by Ho, Martin, and Ruf (1981), on the basis of energetic requirements for NH_3 excitation.

The spiral NGC 6946 has a moderately active nonthermal nuclear source, with a flux density of 6.0 mJy at 6 cm, which can be compared to 22 mJy for the NGC 253 if it were at the distance of NGC 6946. The extent of the smooth nonthermal disk emission can be compared to that of NGC 253 by computing the radius at a given flux density: the 360 pc extent at 0.5 mJy of NGC 253 can be compared to the 120–150 pc extent of NGC 6946 at the same flux level. We have compared our radio map to an Hα photograph of the central region of NGC 6946 (J. Goad, private communication) and have confirmed the weak thermal features through the presence of their Hα counterparts. It is clear from the weakness of the total thermal flux derived for this galaxy that this direct method of detecting young stars is limited to the very nearest galaxies.

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