DECREASING DENSITY GRADIENTS IN CIRCUMNUCLEAR H II REGIONS OF BARRED GALAXIES
NGC 1022, NGC 1326, AND NGC 4314

José Franco, J. Antonio García-Barreto, and Eduardo de la Fuente

Received 2000 February 15; accepted 2000 June 27

ABSTRACT

A reanalysis of the radio continuum emission from circumnuclear regions of the barred galaxies NGC 1022, NGC 1326, and NGC 4314 is presented. The spatial distributions of Hα and radio continuum are similar and suggest the existence of several giant H II regions in the circumnuclear zone. The spectral indices of the H II regions, obtained with similar angular resolution and at three different wavelengths, indicate that in all three galaxies $n_\beta > -0.1$. This result suggests the existence of giant H II regions with decreasing density gradients. The average density stratifications of these H II regions could be approximated by power laws of the form $n_\beta \propto r^{-\alpha}$, with exponents in the range $1.6 < \alpha < 2.4$.

Subject headings: galaxies: ISM — galaxies: spiral — H II regions

1. INTRODUCTION

The average density profiles of extragalactic H II regions can be derived from their thermal radio emission. The thermal radio continuum emission of optically thin photoionized plasma with $\tau_{ff} < 1$ has a relatively flat spectrum with $S_\nu \propto \nu^{-0.3}$, and it changes to $S_\nu \propto \nu^{2}$ when the region becomes optically thick, with $\tau_{ff} > 1$, and has a sharp boundary (e.g., Mezger, Schraml, & Terzian 1967; Mezger & Henderson 1967). When the electron density varies with distance, say, as a power law with $n_e \propto r^{-\alpha}$, and the plasma is optically thick near the center of the emitting object (e.g., ionized stellar winds or dense photoionized molecular clouds), the spectral index varies as $S_\nu \propto \nu^{\alpha}$, with $-0.1 < \alpha < +2$ for $\omega$ ranging from 0 to $\infty$ (Olson 1975; Panagia & Felli 1975). This behavior is indeed observed in stars with extended winds (e.g., Simon et al. 1983) and in some galactic ultracompact and super-ultracompact H II regions (Franco et al. 2000). In particular, the radio continuum emission of the core of galactic source G35.20–1.74 scales as $S_\nu \propto \nu^{0.0-0.6}$, indicating that its internal density structure is proportional to $r^{-2}$ (Kurtz 2000; Franco et al. 2000).

Here, evidence is given that the average density profile of extragalactic H II regions can indeed be derived from the radio continuum, and we discuss the radio emission from the circumnuclear regions in three barred galaxies: NGC 1022, NGC 1326, and NGC 4314. Their Hα and radio continuum emission at 20, 6, and 2 cm, along with CO, H I, and near-IR have been reported by García-Barreto al. (1991a, 1991b, 1991c, 1996). In this paper we reanalyze the radio continuum data and report the spectral indices of the radio continuum emission from several sources in the circumnuclear regions of these galaxies. Their spectral indices between 20, 6, and 2 cm, with observations at the same angular resolution, indicate contributions from both synchrotron and free-free emission. Our results indicate (1) the existence of several circumnuclear H II regions with radio continuum spectral indices $n_\beta > -0.1$, and (2) that the spectral index between 6 and 2 cm from each of the circumnuclear H II regions can be explained if the photoionized gas is optically thick and has a decreasing density structure with a power-law form $n_\beta \propto r^{-\alpha}$, where the exponent is in the range $1.6 < \alpha < 2.4$.

2. THE IONIZED GAS IN NGC 1022, NGC 1326, AND NGC 4314

NGC 1022 is an SBa(r)p barred spiral galaxy located in the Cetus-Aries group of galaxies, at a distance of 18.5 Mpc ($H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$; Tully 1988). The radio continuum emission at 20, 6, and 2 cm (with the same angular resolutions), CO (1–0) and CO (2–1) emission, and near IR with a single element detector have been reported by Garcia-Barreto et al. (1991c). NGC 1326 is an RSbarred spiral galaxy in the Fornax I cluster of galaxies at a distance of 16.9 Mpc (Tully 1988). Radio continuum emission at 20, 6, and 2 cm, CO (1–0) and CO (2–1) emission, and optical spectroscopy have been reported by García-Barreto et al. (1991a). NGC 4314 is an SB(a) barred spiral galaxy in the Coma I group of galaxies, at an adopted distance of 10 Mpc. Radio continuum emission at 20, 6, and 2 cm, H I, CO (1–0) and CO (2–1) emission, and near IR with a single element detector, have been reported by García-Barreto et al. (1991b). Images of the optical continuum in the $f$ filter (8040 Å) and continuum-free Hα + [N II] of these three galaxies have been reported by Garcia-Barreto et al. (1996).

Here we will focus on the properties of the radio continuum emission of the different sources in the circumnuclear regions. In all three galaxies the Hα + [N II] and the radio continuum coincide spatially, indicating that the emission is associated with the star formation process. The radio continuum emission maps were obtained at the (Very Large Array) VLA with similar high angular resolution beams at 20, 6, and 2 cm in order to do spectral index analysis of similar regions at the three wavelengths (García-Barreto et al. 1991a, 1991b, 1991c). The Hα line emission images were obtained with a CCD camera at the 2.1 m telescope in San Pedro Mártir, B.C. México (García-Barreto et al. 1996).

Figure 1 is a superposition of the radio continuum emission at 2 cm on the Hz emission of NGC 1022. Both the radio continuum and Hz-emitting regions are distributed in a similar manner: there is a bright emission region coincident with the compact nucleus, and there are two additional compact sources off-nucleus (to the northeast and slightly northwest). We have labeled them as NGC...
Radio continuum emission at 2 cm (contours) superimposed on the Hα emission (gray scale) of NGC 1022 (from García-Barreto et al. 1991c, 1996). Gray scale: $2.6 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ beam$^{-1}$. Contours: 2.5, 3, 4, 6, 7, 11, 15, 17, 19, 23, 27, and 31 times 150 $\mu$Jy beam$^{-1}$ (rms noise is 150 $\mu$Jy beam$^{-1}$). Restoring beam FWHM at P.A. $D\equiv 11^\circ$, corresponding to a linear scale of 335 pc $\times$ 135 pc.

Fig. 1.—Radio continuum emission at 2 cm (contours) superimposed on the Hα emission (gray scale) of NGC 1022 (from García-Barreto et al. 1991c). Gray scale: 2.6-170 $\times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ beam$^{-1}$. Contours: 2.5, 3, 4, 6, 7, 11, 15, 17, 19, 23, 27, and 31 times 150 $\mu$Jy beam$^{-1}$ (rms noise is 150 $\mu$Jy beam$^{-1}$). Restoring beam FWHM $\approx 37 \times 15$ at P.A. $\approx -11^\circ$, corresponding to a linear scale of 335 pc $\times$ 135 pc.

1022:FGF 1 (nucleus), 2 (to the northeast), and 3 (to the northwest), respectively (see Fig. 1 and Table 1). In the original analysis, done in 1991, only the two strongest sources, 1 and 2, were considered in the radio continuum analysis (García-Barreto et al. 1991c); however, analysis of the Hα distribution suggested weak emission from a source to the northwest (see Fig. 1 and García-Barreto et al. 1996), and a closer inspection of the radio continuum maps also indicated the existence of source 3 at the same location. At larger scales, Figure 2 shows that the radio continuum emission is found only in the central regions of the disk. The image shows the optical I continuum superimposed on the radio continuum at 20 cm. Notice that the position angle of the continuum emission between source 1 (the nucleus) and source 2 is almost perpendicular to the position angle of the stellar bar (P.A.$_{\text{radio}} \approx 25^\circ$ vs. P.A.$_{\text{bar}} \approx 115^\circ$). Also, source 3 (northwest) coincides with a region of distorted isophotes in the optical continuum at P.A. $\sim -30^\circ$.

Figures 3 and 4 reproduce the 2 cm radio continuum emission from the circumnuclear structures in NGC 1326 and NGC 4314. The source designations are given in Table 1. The locations of these structures indicate that they are most likely the result of gas concentrations near (or at) an inner Lindblad resonance (ILR) due to the dynamics driven

| Galaxy     | Source         | Description       | $a^{10}_0$  | $a^0_2$  | $\omega^*$ |
|------------|----------------|-------------------|-------------|-----------|------------|
| NGC 1022   | NGC 1022:FGF 1 | Compact nucleus   | $-0.83 \pm 0.03$ | $+0.12 \pm 0.03$ | 1.62       |
|            | NGC 1022:FGF 2 | Northeast source  | $-0.6 \pm 0.1$  | $+0.15 \pm 0.05$ | 1.63       |
|            | NGC 1022:FGF 3 | Northwest source  | $-0.9 \pm 0.3$  | $+0.9 \pm 0.3$  | 2.41       |
| NGC 1326   | NGC 1326:FGF 1 | Western source    | $-0.67 \pm 0.03$ | $+0.06 \pm 0.05$ | 1.58       |
| NGC 4314   | NGC 4314:FGF 1 | North source      | $-0.83 \pm 0.04$ | $+0.26 \pm 0.03$ | 1.70       |
|            | NGC 4314:FGF 2 | Northeast source  | $-0.82 \pm 0.2$  | $+0.23 \pm 0.2$  | 1.68       |
|            | NGC 4314:FGF 3 | Southeast source  | $-0.63 \pm 0.05$ | $+0.18 \pm 0.1$  | 1.65       |

$^a\omega$ is the exponent of the density distribution $n \propto r^{-\omega}$.

$^b$ Source also known as NWSS J023832$-$064039 (Condon et al. 1998).
by the nonaxisymmetric potential of the bar (Schwarz 1984). For instance, for a bar angular speed of 36 km s\(^{-1}\) kpc\(^{-1}\) in NGC 4314, the ILR could be at a distance of \sim 450 pc from the galactic center, and, for a bar angular speed of 60 km s\(^{-1}\) kpc\(^{-1}\), the ILR in NGC 1326 could be located between 200 and 400 pc from the center (see García-Barreto et al. 1991a, 1991b). Gas accumulates near the resonance, massive stars are then formed and giant H\(_{II}\) regions are created by the strong photoionization field from these newly formed massive stars.

3. SPECTRAL INDEX OF THE RADIO CONTINUUM CIRCUMNUCLEAR SOURCES

We have redone the maps (see Figs. 1, 3, and 4), and rederived the spectral indices between 20 and 6 cm, and 6 and 2 cm. These indices were computed from the peak fluxes, determined from Gaussian fits made with the task IMFIT in AIPS. In the case of NGC 1022, the linear resolution was 335 by 135 pc and the average spectral indices for the compact nucleus and northeast source between 6 and 2 cm are \(\alpha_6 \approx +0.12\) and \(+0.15\), respectively. In contrast, we find \(\alpha_6 \approx +0.9\) for the northwest source. For NGC 1326 the linear resolutions are 295 by 245 pc and the spectral index is \(\alpha_6 \approx +0.06\), and for NGC 4314 the linear resolutions are 195 by 155 pc and the spectral index values are \(\alpha_6 \approx +0.2\). The values for all regions are given in Table 1. Only the strongest sources, with flux densities at 2 cm larger than 5 times the rms noise values, are considered. Also, our observations do not resolve individual (compact or giant) H\(_{II}\) regions, since their average size (less than 100 pc) is smaller than our resolution in all three galaxies.

The spectral index between 20 and 6 cm is negative in all cases, indicating that the emission in this wavelength range has a nonthermal origin. In contrast, the spectral index from 6 to 2 cm is always positive, suggesting that this emission is dominated by thermal bremsstrahlung. This is a consequence of optically thin synchrotron radiation having \(\alpha_6 \approx -0.8\) (Niklas, Klein, & Wielebinski 1997) and thermal bremsstrahlung having \(\alpha \approx -0.1\) and \(+2\), depending on the optical depth (e.g., Mezger & Henderson 1967). Clearly, the values of \(\alpha_6\) for all circumnuclear sources in the three galaxies are within the range of thermal emission, \(-0.1 < \alpha_6 < +2\) (see Table 1). The total radio continuum flux at these wavelengths is the sum of synchrotron and free-free emission. However, a detailed decomposition of the fluxes obtained with similar beams for NGC 1326 by García-Barreto et al. (1991a) indicates a very small synchrotron contribution at 2 cm. A similar exercise with the other sources provides the same result. The synchrotron emission

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**Fig. 2.** Optical continuum emission from the central region of NGC 1022 (contours) superimposed on the radio continuum emission at 20 cm (gray scale) (images taken from García-Barreto et al. 1991c, 1996). Gray scale: 0.3–10 mJy beam\(^{-1}\). Contours (in arbitrary brightness units of 10): 9, 9.5, 10, 10.5, 11, 11.5, 12, 12.5, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 27.5, 30, 40, and 50.
probably falls more rapidly than the free-free emission rises between 6 and 2 cm, and the positive index values are lower limits (but likely close) to the true free-free spectral indices. This is clearly seen in Figure 5, which shows $S_\nu$ versus $\nu$ for all the sources listed in Table 1: (1) the emission between 20 and 6 cm falls down less rapidly than typical nonthermal emission (Niklas et al. 1997), indicating an important thermal contribution at 6 cm, and (2) the extrapolation of the nonthermal component at 2 cm is a small fraction of the actual emission.

The lower limits to the average electron density values of the emitting regions are $50 \, \text{cm}^{-3}$ for NGC 1022 (García-Barreto et al. 1991c), $8 \, \text{cm}^{-3}$ for NGC 1326 (García-Barreto et al. 1991a), and $25 \, \text{cm}^{-3}$ for NGC 4314 (García-Barreto et al. 1991b). These values are similar to the average electron densities, around $10 \, \text{cm}^{-3}$, reported for the circumnuclear starburst in NGC 1097 (Hummel, van der Hulst, & Keel 1987), and to those reported for the giant H II region W3A, within 1 and 80 cm$^{-3}$ (Kantharia, Anantharamaiah, & Goss 1998).

4. DISCUSSION

The spectral indices for the circumnuclear regions in our three barred galaxies are $\alpha_2 > -0.1$, and they have similar spatial distributions in the Hα, CO, and radio continuum emission (García-Barreto et al. 1991a, 1991b, 1991c; Benedict, Smith, & Kenney 1996). This indicates that massive star formation is going on in the giant molecular cloud complexes of the observed regions.

Molecular cloud complexes in our Galaxy display highly irregular density and velocity distributions, giving the impression of conglomerates of high-density condensations, or cloud cores, interconnected by a more tenuous intercore medium. These high-density condensations seem to be the actual sites of massive star formation and they host many of the known ultracompact (UC) H II and super-ultracompact (SUC) H II regions (e.g., Cesaroni et al. 1999; Kurtz et al. 2000). During the formation phase of an H II region, the radiation field creates an ionization front that evolves within the density profile of the star-forming core. The initial structure and early expansion phases of the recently formed H II region, then, are defined by the properties of the star-forming core (Franco, Tenorio-Tagle, & Bodenheimer 1989, 1990). Observations of nearby cloud fragments and extinction studies in dark clouds indicate density distributions proportional to $r^{-\omega}$, with $\omega$ ranging from 1 to 3 and having an average of $\omega \sim 2$ (e.g., Arquilla & Goldsmith 1985; Gregorio Hetem, Sanzovo, & Lepine 1988). For decreasing density gradients with $\omega \geq 1.5$, the ionization front eventually overtakes the shock front and a large
region around the core also becomes ionized. All parts of the cloud core are set into motion, sometimes driving internal shocks, and instabilities in both the ionization and the shock fronts generate clumps and finger-like structures (García-Segura & Franco 1996; Franco et al. 1998; Williams 1999; T. Freyer 2000, in preparation).

The disruptive effects of photoionization and photodissociation first halt the star formation activity (Franco, Shore, & Tenorio-Tagle 1994; Diaz-Miller, Franco, & Shore 1998) and later, once a large fraction of the parental cloud is ionized, accelerate outflows in an expanding giant H II region. The combined action of photoionization and the strong mechanical energy input from stellar winds and supernova explosions, then, eventually destroys the molecular cloud complex and creates large expanding shells (see reviews by Yorke 1986, Tenorio-Tagle & Bodenheimer 1988, and Bisnovatyi-Kogan & Silich 1995). Thus, the nonthermal and thermal radio continuum emission from the circumnuclear regions of the three barred galaxies can be viewed as resulting from the stellar energy input that is destroying the parental clouds. The negative spectral index between 20 and 6 cm (except for the compact nucleus of NGC 1022) is likely due to nonthermal emission from supernovae (SNe) associated with the star-forming activity. The positive index between 6 and 2 cm, on the other hand, is likely due to optically thick thermal emission from the expanding H II regions.

The spectra of the free-free emission from an optically thick plasma with various decreasing density stratifications have been calculated by Olnon (1975) and Panagia & Felli (1975). The main result of these studies is that, for unresolved sources, the spectral index is in the range from $-0.1$ to $+2$, depending on the particular functional form of the density gradient and the optical depth of the region. For a power law of the form $n_e \propto r^{-\alpha}$, the value of the spectral index $\alpha$, $\tau_\nu \propto \nu^\alpha$, depends on the exponent $\alpha$ as (Olnon 1975)

$$\alpha = (2\omega - 3.1)/(\omega - 0.5) .$$

For a truncated power law (which removes the pole $n_e \to \infty$ at $r \to 0$) and other functional forms for the density stratification, the formulae for the spectral index become more complicated. For simplicity, and following the results from nearby clouds, the power-law case can be used as an approximation to the plasma density stratification. Thus, the photoionized circumnuclear clouds detected in the radio continuum can be characterized by exponents in the

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**Fig. 4**—Radio continuum emission at 2 cm (contours and gray scale) of NGC 4314 taken from García-Barreto et al. (1991a). Gray scale: 45–320 $\mu$Jy beam$^{-1}$. Contours: -2, 2, 2.5, 3, 4, 5, 5.5, 6, 6.5, and 7 times 45 $\mu$Jy beam$^{-1}$ (rms noise is 45 $\mu$Jy beam$^{-1}$). Restoring beam FWHM $\sim 3^\prime.9 \times 3^\prime.1$ at P.A. $\sim 90^\circ$ corresponding to a linear scale of 195 pc $\times$ 155 pc.
range $1.6 < \omega < 2.4$ (the values of $\omega$ for all sources are listed in Table 1). It is important to emphasize, as the referee has pointed out, that these giant extragalactic H\textsc{ii} regions are usually composed of a collection of individual ionized cores embedded in a lower brightness extended region. Thus, the density gradients derived from the spectral index measurements represent an average density stratification which may be different from the actual density profiles of the individual ionized cores.

Summarizing, the radio continuum emission from the circumnuclear regions in the three barred galaxies NGC 1022, NGC 1326, and NGC 4314 show a combination of non-thermal and thermal features. The fact that all observed sources have similar properties, a negative index value between 20 and 6 cm and a positive value between 6 and 2 cm, indicates that the radio emission is mainly due to SN and H\textsc{ii} regions in massive star-forming regions. In particular, the free-free emission of the unresolved giant H\textsc{ii} regions indicates density gradients shallower than $\omega \sim 2.5$. This result is similar to the one reported by Franco et al (2000) for ultracompact H\textsc{ii} regions, and suggests that many H\textsc{ii} regions, in our Galaxy and in other galaxies, are optically thick at radio wavelengths and may provide information of the density stratification of the emitting plasma. This was already hinted at by the reported spectral indices greater than $-0.1$ in both giant and ultracompact H\textsc{ii} regions (Wood & Churchwell 1989; Kantharia et al. 1998), and suggests that further analysis of the data may provide valuable information about the properties of star-forming regions.

It is a pleasure to thank Stan Kurtz for many stimulating and informative discussions, and an anonymous referee for useful suggestions that helped us to improve the contents of the paper. J. F. acknowledges partial support by DGAPA-UNAM grant IN130698 and by a R&D CRAY research grant. E. de la F. wishes to acknowledge financial support from CONACyT-México grant 124449 and DGEP-UNAM through graduate scholarships.

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