RADIO CONTINUUM EMISSION FROM THE NUCLEI OF NORMAL GALAXIES

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1. INTRODUCTION

During the last few years detailed and sensitive observations of the radio emission from the nuclei of many normal spiral galaxies has become available. Observations from the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO[1]), in particular, enable us to distinguish details on a scale of $\lesssim$100 pc for galaxies at distances less than 21 Mpc. The best studied nucleus, however, still is the center of our own Galaxy (see Oort 1977 and references therein). Its radio structure is complex. It consists of an extended non-thermal component 200 x 70 pc in size, with embedded therein several giant HII regions and the central source Sgr A (~9 pc in size). Sgr A itself consists of a thermal source, Sgr A West, located at the center of the Galaxy, and a weaker, non-thermal source, Sgr A East. Sgr A West moreover contains a weak, extremely compact ($\lesssim$10 AU) source. The radio morphology of several other galactic nuclei is quite similar to that of the Galactic Center, as will be discussed in section 2. Recent reviews of the radio properties of the nuclei of normal galaxies have been given by Ekers (1978a,b) and De Bruyn (1978). The latter author, however, concentrates on galaxies with either active nuclei or an unusual radio morphology. In this paper I will describe recent results from the Westerbork Synthesis Radio Telescope (WSRT, Hummel 1979), the NRAO 3-element interferometer (Carlson, 1977; Condon and Dressel 1978), and the VLA (Heckman et al., 1979; Van der Hulst et al., 1979). I will discuss the nuclear radio morphology in section 2, the luminosities in section 3, and the spectra in section 4. In section 5 I will briefly comment upon the possible implications for the physical processes in the nuclei that are responsible for the radio emission.

2. THE RADIO MORPHOLOGY OF NUCLEAR SOURCES

Until recently it has not been possible to resolve the radio emission from galactic nuclei, with the exception of a few nearby galaxies (e.g. M31 [van der Kruit 1972], M51 [Spencer 1973], NGC 253 [Becklin et al., 1972]). However, observations at λ6cm of 81 galaxies

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with the VLA (Van der Hulst et al., 1979) now provide information on the radio morphology of nuclear sources. Two to three short observations, each at a different position angle, were obtained for each galaxy. These provide good information for simple nuclear sources. It is also possible to conclude whether nuclei have a complex brightness distribution, although for detailed information full coverage mapping is required. Sixty-one galaxies were positively detected, of which only 13 are still unresolved. This sample is a subset of all nuclei detected in previous surveys (De Bruyn 1976; Crane 1976; Hummel 1979); it was selected in such a way as to ensure an optimum coverage of all morphological galaxy types. Galaxies of type Scd through I are, however, somewhat underrepresented as a result of the lower detection rate for these galaxy types (Condon and Dressel 1978; Hummel 1979).

In order to examine the radio structure we defined four categories: (i) nuclear sources that can best be represented by a simple Gaussian brightness distribution; (ii) sources with a small central component and a weaker, more extended Gaussian component centered at the same position (the core-halo sources); (iii) sources which besides a central component have an extended, complex brightness distribution; and (iv) galaxies without a distinct nuclear source stronger than ~1.5 mJy (1 mJy = 10^{-29} W m^{-2} Hz^{-1}). Figure 1 shows for each revised Hubble type (de Vaucouleurs et al., 1976) the fraction of nuclei in each category. An interesting trend is apparent: galaxies of type Sb or later predominantly have complex nuclear sources, if one at all; galaxies of type Sab or earlier mostly have simple nuclear sources, whereas core-halo sources occur in galaxies of intermediate type (SO-Sc). The peculiar and elliptical galaxies (hatched) are only included for comparison. A similar trend exists with Yerkes form type (Morgan 1958, 1959). The k-g type galaxies have simple nuclei, while core-halo and complex nuclei are mostly found in gf-a type galaxies. This is not so surprising because of the known relation between the Hubble and Yerkes form classifications. Our own Galaxy (probably Sbc) has a complex radio nucleus, in good agreement with the trend present in Fig. 1. Some of the galaxies with complex emission do have radio features that correspond to optical condensations in the nuclei. These condensations may very well be giant, nuclear HII regions

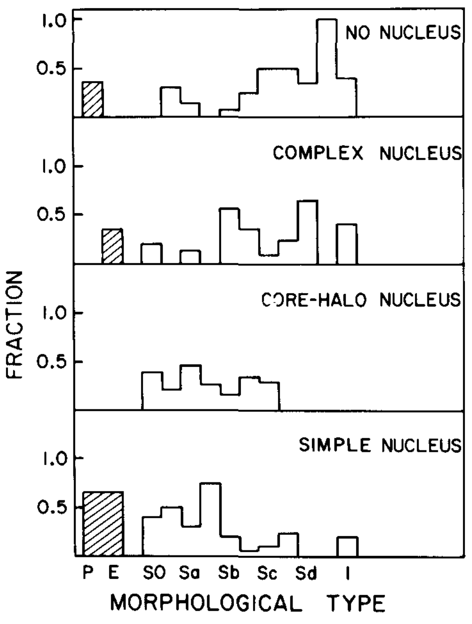

Fig. 1 Distribution with Hubble type of nuclei in each of four radio morphology categories.

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(Schmidt-Kaler 1975; Ulrich 1975; Heckman 1979a,b). Examples are NGC 1097, 2903 and 4321.

The linear diameters of the central sources are shown in Figure 2 (only spiral galaxies). Upper limits are hatched. I added results from Heckman et al. (1979), Crane (1977) and Carlson (1977). Distances are from Sandage and Tammann (1974) or otherwise calculated with H = 55 km/sec/Mpc. The median size is ~150 pc. That this is smaller than previously thought (Ekers 1974, 1975, 1978b) can be attributed to confusion with the more extended emission in earlier, lower resolution surveys. Of all nuclei smaller than 150 pc, 45% are unresolved and may very well have dimensions less than ~9 pc, the size of the Sgr A component in the Galactic Center. VLBI observations of 31 galaxies by Crane (1979) do indeed show that ~8 out of 20 S0-Sb galaxies have nuclear components less than 1 pc in size. The extended halo and complex components range from ~200 pc to several kpc in size. The sample in Fig. 2 includes 10 Seyfert and 18 interacting galaxies. The radio size distribution for each of these groups is not significantly different from the size distribution for normal galaxy nuclei. The larger sample of Seyfert galaxies of De Bruyn and Wilson (1978) corroborates this conclusion.

No correlation exists between the radio size of a nucleus and the morphological type of a galaxy, the absolute magnitude, or the nuclear radio power. However, one interesting effect was found: half of the central sources in Yerkes form type g, gk and k galaxies are smaller than 100 pc, whereas in all other Yerkes type galaxies this fraction is only 15-30%. Heckman (1979a,b) identifies 13 compact ($\lesssim 1\rlap{.}''7$) nuclear sources in his sample and finds that all of these occur in early type galaxies whose nuclei have an old, metal rich stellar population and exhibit low excitation emission line spectra (see Heckman, this volume). Remarkably, 62% of these galaxies are of Yerkes form type k.

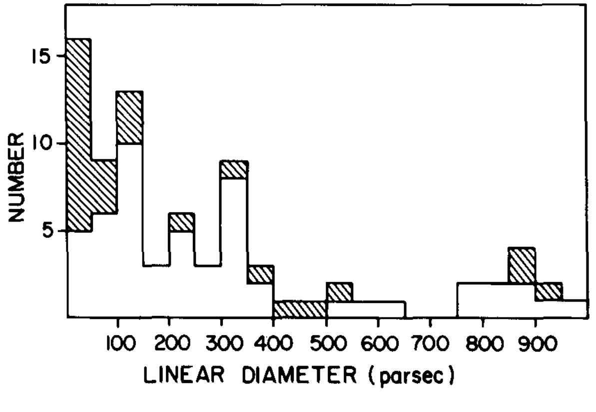

Fig. 2 Distribution of sizes of nuclear sources in spiral galaxies.

3. THE RADIO LUMINOSITY OF NUCLEAR SOURCES

The limited VLA sample of radio nuclei does not allow studies of the radio luminosity function. The large surveys of Crane (1976) and Hummel (1979) however do and lead to the following results. Crane concludes that the radio luminosity function for nuclei and the optical luminosity function have the same slope, though at the bright end this result depends on whether the Seyfert galaxy NGC 1068 is included. Hummel investigated the fractional (integral) luminosity function for nuclear sources. He concludes that in general central sources contribute less than 10% to the total monochromatic power of a galaxy at 1415 MHz. Although the VLA sample corroborates this result, we find that 20% of the nuclei contribute more than 50% to the total power. These are all Sbc or earlier type galaxies, which is not surprising because early type galaxies have in general strong nuclear emission and weak radio disks, whereas the opposite is true for late type galaxies (Hummel 1979). Hummel furthermore finds that the nuclear radio power depends on Hubble type; especially the Scd through Sm galaxies have very weak ($P < 10^{20}$ W Hz^{-1} $Ster^{-1}$ at 1415 MHz) radio nuclei. This trend is also obvious from the VLA sample as discussed below, though within a given Hubble type the nuclear radio power can vary by three orders of magnitude. The ratio of nuclear radio power to total optical luminosity (R, as defined by Condon and Dressel 1978) has a much stronger dependence on galaxy type. R decreases from 43 for S0/a galaxies to 2 for Scd and later type galaxies (Hummel 1979).

A very interesting result is that the nuclear sources in barred spirals are on the average brighter than those in non-barred spirals. This is not true for the total radio power. Condon and Dressel (1978) did not find this effect, probably due to the smaller sample size. They do, however, note that the majority of their compact ($\lesssim 6''$) nuclear sources occur in paired galaxies. Hummel finds that on the average nuclear sources in double galaxies are brighter than in isolated galaxies. Stocke (1978) studied the total emission in double galaxies and finds that their detection rate is not only higher than for isolated galaxies, but also increases with decreasing linear separation between the galaxies in a pair.

The above results refer to both the small central sources and the more extended, complex and halo components (sect. 2), when present, owing to the ~25" (1 kpc at 8.3 Mpc distance) WSRT resolution at 1415 MHz. Let us therefore examine the small central sources a little closer. The fraction of the total nuclear flux in the central component is about 0.4 on the average, though for individual galaxies it may be as small as 0.1 or as large as 0.8. The VLA sample, however, does not allow precise statements concerning how this may affect the luminosity function as derived by Hummel. Figure 3 shows the nuclear power for 83 galaxies observed with the VLA at 6cm (Van der Hulst <u>et al.</u>, 1979; Heckman <u>et al.</u>, 1979) as a function of Hubble type. Seyfert and interacting galaxies are indicated as crosses and open circles respectively. That the average power decreases with type when going from S0 to I is evident. The peculiar and elliptical galaxies are only included for comparison. Note however the large range in power within each galaxy type, especially Sb and earlier. For comparison, the whole Galactic Center complex has a 6cm radio power of $\sim 10^{18.3}$ W Hz^{-1} $Ster^{-1}$, the 10 pc Sgr A source a power of $\sim 10^{17.3}$ W Hz^{-1} $Ster^{-1}$, and the compact source in Sgr A west a power of only $\sim 10^{14.7}$ W Hz^{-1} $Ster^{-1}$. In other words: the galactic nuclei in Fig. 3 are all stronger than the Galactic Center, though their radio sizes are comparable or smaller.

It is of interest to note that the radio power of the giant HII regions in M101 (Israel et al., 1975) is about $10^{18.8}$ W Hz^{-1} $Ster^{-1}$, similar to the luminosity of the nuclei in the Sd and I galaxies. With 20cm VLA observations, planned for late 1979, we will be able to determine whether these sources are thermal. The 10 Seyferts in the sample have on the average brighter nuclei, a notable exception being NGC 4051 with only P = $10^{18.8}$ W Hz^{-1} $Ster^{-1}$. It is not possible, however, to distinguish Seyfert from non-Seyfert galaxies on the basis of their radio properties alone as was also noted by Carlson (1977).

The interacting galaxies do not clearly stand out as being brighter, with two notable exceptions: NGC 3690 (Mk 171) and NGC 1614 (Mk 617, Arp 186). NGC 3690 has a double nucleus and the strong radio emission is associated with the eastern optical component (Sramek and Tovmassian 1976). One might speculate that this is a case of two merging galaxies (Toomre 1977). NGC 1614 is a much stronger candidate for merging. This system resembles NGC 4038/39 (also a strong radio emitter [Burke and Miley 1973; Van der Hulst 1979]): it has two faint tails, a double nucleus, and the radio emission is centered between the two nuclei. Two more such examples are NGC 6090 (Van der Hulst et al., 1979) and NGC 2623 A/B/C (Condon and Dressel 1978).

The radio power of the nuclei is weakly correlated with absolute magnitude. This correlation does not significantly improve when nuclear magnitudes (Keel and Weedman 1978) are used. Hummel (1979) finds that for sample means the radio power is proportional to the optical luminosity: $P \propto L^{1.0\pm0.2}$. No other significant correlations have yet been found between nuclear radio power and other properties of a galaxy such as color, HI content or dynamical parameters. However, especially information concerning the central gas density and the dynamics in the inner regions of galaxies is currently available for only a limited number of the objects in the various surveys. A long known exception to the above is the correlation between nuclear radio power and 10μ infrared power, first discovered for Seyfert galaxies (van der Kruit 1971, 1973; Rieke and Low 1972; De Bruyn and Wilson 1978; Rieke 1978). IR fluxes are available for 11 of the non-Seyfert galaxies in the VLA sample, and upper limits for 7. That these galaxies also obey the radio-IR relation of Seyfert and

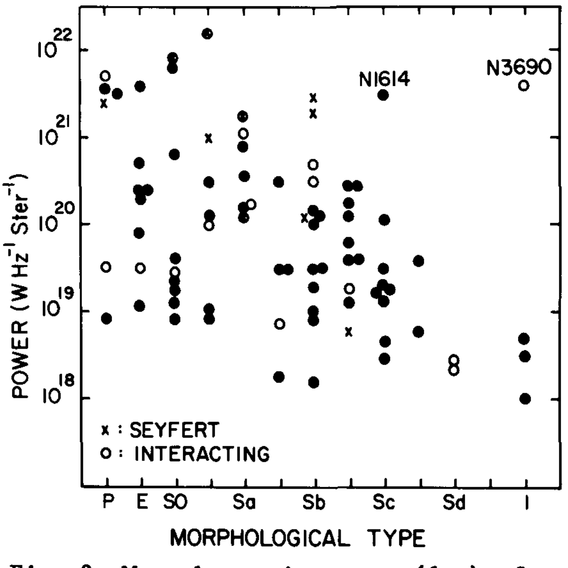

Fig. 3 Monochromatic power (6cm) of nuclei as a function of Hubble type.

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emission line galaxies (i.e. S(IR)/S(radio) = 3-30) lends support to the earlier notion that this correlation is not peculiar to active galaxies alone. The cause of this correlation is still unclear.

4. THE SPECTRA OF NUCLEAR SOURCES

Spectral information is available for ~50 nuclei (Crane 1976; Carlson 1977; Condon and Dressel 1978; Heckman et al., 1979). Except for Heckman's data, the spectra refer to both the small central sources and the extended components, when present. The distribution of spectral indices is broad, with a peak around $\alpha \simeq -0.7$ ($S \propto \nu^{\alpha}$), and ranging from $\alpha \simeq -0.1$ to $\alpha \simeq -1.2$, not significantly different from the result shown by Ekers (1978, Fig. 2c) for about 26 nuclei. However, the number of spiral galaxies with very compact, flat spectrum nuclear sources has increased from two (M81 and M104, De Bruyn et al., 1976) to at least ~7, now also including NGC 3310, 3718, 3998, 5675 and 6500 (Carlson 1977; Heckman et al., 1979; Crane 1979).

Because most surveys include the extended nuclear components, it is not possible to combine these with the VLA results for determining the spectrum of the small nuclear components. However, the future 20cm observations with the VLA will provide good spectral indices and, moreover, allow a determination of the spectrum of the extended components. Especially when the complex emission appears to be associated with nuclear HII regions it is of interest to investigate whether a spectral flattening, due to thermal emission, is present. For example, in NGC 6946 the extended nuclear component may have a large thermal contribution (Van der Kruit et al., 1977).

5. DISCUSSION

Though much more information has become available on the continuum properties of central sources in spiral galaxies, our knowledge of the nature of the nuclear engine is still quite poor. Obviously we will not be able to unravel this problem on the basis of radio observations alone. Data from other spectral domains are extremely important and also becoming more numerous. In the past various mechanisms have been suggested, such as frequent supernova explosions, massive star formation, the presence of a massive object, e.g., a giant pulsar or a black hole. A few things can be said about these possibilities, though final conclusions require continued research. The possibility of frequent supernovae is not very attractive. Radio surveys of SN remnants in external galaxies (De Bruyn 1973; Brown and Marscher 1978) have been very unsuccessful. Even in quite nearby galaxies no SN remnants were detected. Carlson (1977) concludes that active, i.e. small ($\lesssim$100 pc) and luminous nuclear sources mostly occur in galaxies that are a member of a group and possibly show signs of massive nuclear star formation. Heckman (1979a,b) on the other hand finds that compact nuclear sources are associated with K giant type, metal rich nuclei, which, moreover, exhibit low excitation emission lines. He proposes that a shock wave heats the gas that produces the emission lines. Also, the late type galaxies that have young stars in their nuclei are the ones with the lowest detection rates for nuclear sources.

Condon and Dressel (1978) propose that galaxies may have inactive black holes in their centers that receive a fresh supply of gas as a result of gravitational interaction with another galaxy and consequently increase their radio output. Relating the supply of gas to the strength of nuclear sources is an attractive possibility and may explain that central sources in paired galaxies are brighter. Also the stronger nuclear sources in barred spirals may result from a relatively high supply of gas, because barred spirals have large amounts of gas streaming into their centers (Roberts 1978; Roberts et al., 1979), as opposed to non-barred galaxies. Further evidence should come from a detailed mapping of the gas distribution and motions in the inner regions of such galaxies. The association of compact nuclear sources with early type galaxies, that have in general a deficiency of neutral gas in their central regions does not necessarily contradict this. The emission line spectra indicate the presence of at least ionized gas.

Finally, the evidence for explosive mechanisms in spiral galaxies is not really overwhelming. The only strong case remains NGC 4258 (Van der Kruit et al., 1972; De Bruyn 1977; Van Albada 1977).

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