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The Radio Properties of Seyfert Galaxies

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Summary. The properties of Seyfert galaxies at radio wavelengths are discussed from a statistical point of view. In general, the radio emission is associated with the nucleus of the galaxy and has a steep, non-thermal spectrum. However, at least 10% of optically selected Seyferts exhibit a flat spectrum, very compact, core source. For the steep spectrum sources, direct resolution of the radio nucleus in several of the more nearby galaxies implies that the radio source is generally of order several hundreds of parsecs to a few kiloparsecs in extent, comparable in scale with the forbidden line region. Double radio sources outside the optical boundaries of the galaxies are not found associated with optically selected Seyferts. Although there is no significant difference between the histograms of spectral index for Type 1 and Type 2 galaxies, the Type 2's are, in general, more luminous at λ 21 cm than the Type 1's. This last result is used to argue that either transitions from typical Type 1 to typical Type 2 Seyferts do not occur, or, if they do, the time scale for such a transition is $>10^5$–10^6 years.

Relations between the radio, optical, and infrared properties are explored. Correlations appear to exist between the continuum luminosity at λ 21 cm and the luminosity in the [O III] λ 5007 Å line and between the continuum luminosities at λ 21 cm and λ 10 μ, although the latter relation is much looser than previously believed. The former relation is interpreted in terms of a pressure balance between the magnetic field and cosmic rays necessary for the radio emission and the filaments of thermal gas in the forbidden line region. The radio-infrared relation is harder to understand since the infrared radiation in Type 1 Seyferts appears to originate from a much smaller region ($\lesssim 0.1$ pc in extent) than the radio source. It is shown that the relativistic electrons radiating the centimetre radio radiation must be re-accelerated at distances $\gtrsim$ a few parsecs from the nuclear core source, unless they can stream away from it at relativistic speeds.

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1. Introduction and Sample Definition

Seyfert galaxies, defined as galaxies with intense, broad emission lines arising in a stellar or almost stellar nucleus, have been investigated extensively at optical and infrared wavelengths. Because they are relatively unconspicuous at radio wavelengths their radio properties are less well known. Pioneering radio investigations were made by Wade (1968) and van der Kruit (1971). Recent radio surveys of the Markarian galaxies, our richest source of galaxies with Seyfert characteristics, by Sramek and Tovmassian (1975) and Sulentic (1976) have resulted in the detection of 7 more Seyfert galaxies. A more sensitive survey of 43 Seyfert galaxies was recently completed by us in λ 21 cm continuum radiation (de Bruyn and Wilson, 1976, Paper I) and resulted in the detection of 22 galaxies above a flux density of 4 mJy[1]. A summary of the currently available radio data on Seyfert and related galaxies was presented in Tables 4 (Seyfert galaxies) and 5 (galaxies with intense sharp emission lines) of Paper I[2].

In this paper we investigate the statistical properties of the radio emission from Seyfert galaxies and the relation of the radio to the optical and infrared properties. A serious complication in this work is the heterogeneous nature of the methods used to discover these galaxies, so it is appropriate to begin by describing the contents of the sample.

The 61 Seyfert galaxies listed in Table 4 of Paper I comprise:

[1] 1 mJy $=10^{-29}$ Wm^{-2}Hz^{-1}

[2] The following corrections should be applied to Tables 3 and 4 of Paper I. a) The background source listed opposite IIZw23 under "Comments" in Table 3 in fact refers to NGC 7714. b) In Table 4, the value of $P_{1415\,\mathrm{MHz}}$ for IC 4329A should be 4.3 10^{21} WHz^{-1} sterad^{-1}. c) In Table 4, the radio size of NGC 3516 should be $d<4$ kpc

a) all objects in the list of Khachikian and Weedman (1974a) except the 13 galaxies for which no radio data were available and Mark 501, a BL Lac object (Khachikian and Weedman, 1974b), and

b) Mark 106, 205, 463 and NGC 6764, which also satisfy the definition of a Seyfert galaxy given above (note that, although Mark 64, 106 and 205 are considered Seyfert galaxies in this paper, they have a star-like appearance and may also be classified QSO's).

Included in this sample of 61 galaxies are the radio galaxies 3C227, 287.1, 390.3 and PKS 2349-01. However, to avoid the introduction of (unknown) biases in the statistical investigation of radio properties, we exclude them from further consideration since they were shown to be Seyferts *after* their detection as a radio source. Such powerful radio galaxies constitute only a tiny fraction of the Seyfert galaxies in a given volume of space.

The resulting 57 galaxies still form a heterogeneous group of objects from the NGC, Zwicky and Markarian catalogues and is not complete to any given optical magnitude. In fact, the only reasonably complete sample is the 41 Seyferts in the first four lists of Markarian (Huchra and Sargent, 1973). Even this sample is incomplete at low optical luminosities since at least two "classical" Seyferts lie in the region of sky from which these lists were drawn but are not included in them. In addition, many galaxies brighter than the nominal limit on apparent magnitude must have been missed (Huchra and Sargent, 1973). Despite these shortcomings, these 41 galaxies will be used as our basic sample for correlation studies, although occasionally the selection criteria will be relaxed to include all 57 objects in the analysis.

To understand the distinctive properties of Seyfert galaxies, it is necesasry to isolate the radiations associated with the excited "Seyfert" state of the nucleus from components which also exist in the quiescent phase. A large fraction of Seyferts show spiral structure (Adams, 1977) but the radio emission of even low luminosity Seyfert galaxies is concentrated in the central regions (§ 2), in contrast to the situation prevailing in normal spirals (van der Kruit, 1973; de Bruyn, 1976). Thus, although the distribution of radio luminosity of the Seyfert galaxies does overlap at its lower end with that of normal spirals (e.g., Cameron, 1971), it is reasonable to assume that most of the radio emission from the Seyferts is related to nuclear activity. Similarly, the optical continuum, optical line emission and infrared radiation are dominated by the central regions and are generally much stronger than found in normal galaxies. We have, therefore, made no attempt to correct the data for contributions from extranuclear regions.

In §§ 2 and 3 we consider the radio structural and spectral properties, while § 4 deals with the radio luminosities. Correlations of the radio luminosities with optical and infrared properties are the subject of § 5, and in § 6 we discuss the nature of the non-thermal sources in Seyfert galaxies. Some remarks on the continuity between Type 1 Seyfert galaxies and QSO's are given in § 7. As in Paper I, a Hubble constant $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ is assumed.

2. Radio Structure

Because of the large range in both instrumental resolution and distance of the galaxies surveyed, the linear resolution varies enormously. We restrict ourselves, therefore, to some general comments about the type of structure and the relative extent of radio and optical image. For the majority of detected galaxies, the radio source is unresolved. However, many of the nearby NGC (classical) Seyferts have been resolved at radio wavelengths and have been found to have extents of several hundred pc to a few kpc (van der Kruit, 1971; de Bruyn and Willis, 1974; Crane, 1977). With the exception of Mark 6, 78 and 231, 3C120 and NGC 1275, the radio source is smaller than or at most comparable to the optical dimensions. For 25% of the detected galaxies (9 out of 36 in the sample of 57), the linear resolution is sufficient to establish that the radio emission originates within the inner 10% of the optical extent given by Khachikian and Weedman (1974a). Five of the galaxies have a core-halo structure (Mark 6 and 231, NGC 1068 and 1275, and 3C120). In NGC 1068 this "halo" is, however, only about 1 kpc in diameter. In three of these five (NGC 1068 and 1275, 3C120), the core has a flat spectrum and variable flux density. Variable flat spectrum radio cores are also found in Mark 348 and IIIZw2. Hence, at least 10% of all Seyfert galaxies exhibit such a core, whose presence does not seem to be correlated with optical type or luminosity.

An interesting result of the survey reported in Paper I is that none of the detected galaxies are double radio sources. An absence of double sources straddling the optical object also applies to a region of diameter about 0.6 Mpc surrounding the Seyfert galaxies in the sample of 41. We have investigated whether the classical Seyferts also lack extended double structure using the Westerbork data of van der Kruit (1971). With the exception of NGC 5548, which is straddled by sources of 34 and 22 mJy at 1.7 and 4.′1 in position angles 270° and 113°, no double sources with component intensities greater than about 10 mJy were found within a radius of about 15′ which corresponds to 60–250 kpc at the distances of these objects. It is quite probable that the double source straddling NGC 5548 represents a chance alignment of background sources.

3. Radio Spectrum

For 16 of the detected galaxies in the sample of 57 sufficient data exist to determine the radio spectral index. Figure 1 shows a histogram of the distribution of spectral indices α at λ 21 cm [defined as flux density $\propto$ (frequency)$^{\alpha}$]. The three galaxies with spectral indices $\alpha \sim 0$ (3C120, NGC 1275 and Mark 348) all exhibit variable flux density and spectral index. NGC 1068 and Mark 3 have a break in their spectra near 1 GHz where the spectral index changes from $\alpha \simeq -0.3$ (low frequencies) to $\alpha \simeq -0.8$ (high frequencies). The remaining objects have straight spectra to within the errors. Examination of Figure 1 shows that there are no significant differences between the spectral index distributions of Type 1 and Type 2 Seyferts.

Figure 1 indicates that the radio emission from Seyfert galaxies is predominantly non-thermal in origin. Although this is not surprising, it is important to point out that one can also expect a significant thermal radio contribution from the gas which generates the intense optical emission lines. For the approximately twenty Seyfert galaxies for which both the flux density at radio wavelengths and the intensity of Hα emission are known (Paper I; Adams and Weedman, 1975), the expected thermal radio emission is generally between 1 and 10% of that actually observed at λ 21 cm. This estimate is, however, uncertain for the following reasons. Firstly, the true Hα luminosities may be considerably larger because of optical obscuration. Secondly, much of the flux of the optical emission lines may originate in regions optically thick to λ 21 cm radiation (this is certainly the case for the dense cores of Type 1 Seyferts, where the broad wings on the Balmer lines are emitted). The first effect tends to increase the expected thermal radio emission, the second to decrease it. Both effects, in addition to possible self-absorption of Hα itself (Netzer, 1975), should be considered to determine the contamination of the spectrum by thermal radio emission in each individual case.

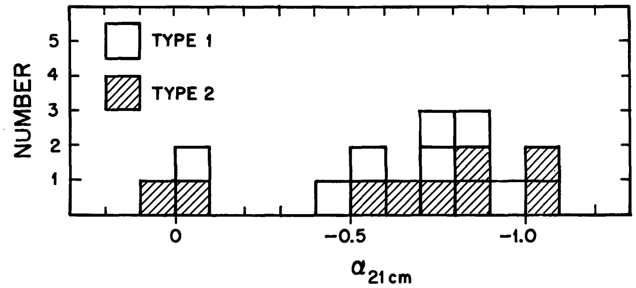

Fig. 1. Histogram of the distribution of spectral index α at λ 21 cm ($S \propto \nu^{\alpha}$) for 16 galaxies in the sample of 57 defined in § 1. Mark 6 is classified as Type 1 (§ 4) and Mark 463 as Type 2 on the basis of a multi-channel scan from the 200-inch Hale telescope (Sargent, unpublished)

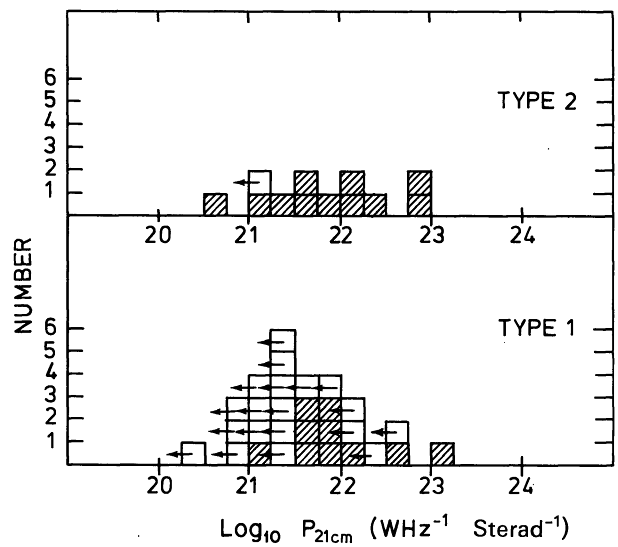

Fig. 2. Histogram of the luminosities at λ 21 cm of the 12 Type 2 (upper diagram) and the 29 Type 1 (lower diagram) Seyfert galaxies which comprise the sample of 41 defined in § 1. Detected galaxies are represented by shaded squares, undetected galaxies by open squares. With the exception given in the caption to Figure 1, the type classification is from Khachikian and Weedman (1974a). Mark 106 and 205, not included in these authors' paper, are of Type 1

4. Radio Luminosity

Figure 2 shows histograms of the luminosities at λ 21 cm of the 29 Type 1 and 12 Type 2 Seyfert galaxies which together comprise the sample of 41. As noted in § 1, this sample may be incomplete at low optical luminosities since several of the "classical" Seyferts are not included. These few classical Seyferts have luminosities in the range $10^{19.5}$ to 10^{21} WHz^{-1} $sterad^{-1}$ at λ 21 cm, weaker than most of the galaxies in the sample of 41.

As may be seen in Figure 2, 10 out of 29 Type 1 and 11 out of 12 Type 2 Seyferts were detected. [Note that Mark 6 has been reclassified as Type 1 (cf. Neugebauer et al., 1976); recently Osterbrock and Koski (1976) have proposed that this galaxy is intermediate between Types 1 and 2.] The average distance of the 29 Type 1 galaxies (276 Mpc) is greater than that of the 12 Type 2's (168 Mpc). However, the lower detection probability of Type 1's in comparison to Type 2's may not be wholly ascribed to a distance selection effect since:

a) of the nearest 16 Type 1 galaxies, whose average distance is 164 Mpc (i.e., close to that of the 12 Type 2's), only 6 were detected, and

b) examination of Figure 2 shows that the undetected Type 1 galaxies have a luminosity at λ 21 cm less than that of most Type 2's.

We conclude that, although the upper bound of luminosity at λ 21 cm is about the same for both types in this sample ($\sim 10^{23}$ WHz^{-1} $sterad^{-1}$), the average luminosity of Type 1 galaxies is less than that of Type 2's, probably by at least a factor of 5. A high sensitivity survey of the undetected Type 1 galaxies is needed to define this factor more accurately. It is interesting to note that the two objects with the highest radio powers among the Type 1 galaxies in the sample of 41 are Mark 6 and 231. As already noted, Mark 6 appears to be of intermediate type, while Mark 231 has many peculiar features (Boksenberg et al., 1977) and its classification as a Seyfert must be in some doubt. A difference in radio luminosity between Types 1 and 2 galaxies was already noted by Sramek and Tovmassian (1975) for a smaller sample.

It is most unlikely that this difference in average luminosity at 1.4 GHz between Types 1 and 2 galaxies is a consequence of greater absorption of the radio radiation in Type 1 Seyferts, for the following reasons. Firstly, if this were the case, one would expect Type 1 galaxies to have, on average, flatter radio spectra because all plausible absorption processes will reduce low-frequency radiation much more than high-frequency radiation. This is in disagreement with the result of § 3. Secondly, the defining difference in the two types is the existence of broad wings on the permitted lines in Type 1's, which are believed to be formed in a dense core ($n_e \gtrsim 10^8\,\mathrm{cm}^{-3}$) of extent ~ 0.01 pc (Adams and Weedman, 1975; Osterbrock et al., 1976). However, as we shall argue in § 6.1, the radio source in most Seyfert galaxies is several hundreds of parsecs in extent and thus too large to be significantly attenuated by free-free absorption in the dense core.

We conclude that the difference in average radio luminosity between Types 1 and 2 reflects a real difference in at least one of the parameters determining the power output in synchrotron radiation (i.e., relativistic electron density, magnetic field strength or overall extent of radio source). This result has interesting consequences for any evolutionary relation between the two types of Seyfert galaxy, as we now discuss. The two distinctive, and possibly only, optical differences between the two types of Seyfert are the presence of broad wings on the permitted lines and non-thermal infrared/optical/ultraviolet continua in Type 1's. Both of these components originate in a small core region <0.1 pc in extent (e.g., Osterbrock, 1971; Penston et al., 1974; Adams and Weedman, 1975; Osterbrock et al., 1976). If the non-thermal source were turned off, the gas emitting the broad wings in the permitted lines would recombine in a time $t_{\mathrm{rec}} = (n_e \alpha_B)^{-1} \simeq 0.5$ days for $n_e = 10^8\,\mathrm{cm}^{-3}$. The light travel time across the region is of the order of a few months or less. Thus, these two distinctive properties of Type 1 galaxies could, in principle, disappear in less than a year (see Tohline and Osterbrock, 1976 for further discussion of the relevant time scales) and the resulting optical spectrum could resemble that of a Type 2 Seyfert. Changes in the intensities of the broad component of the Balmer lines and/or the continuum have been observed in a number of Type 1 Seyferts (e.g., Khachikian and Weedman, 1971; Penston et al., 1974; Quintana et al., 1975; Tohline and Osterbrock, 1976 and references therein). It is also relevant that Osterbrock and Koski(1976) have classified NGC4151 and Mark 6 as internediate between Types 1 and 2. The *optical* data are, therefore, consistent with the occurrence of transitions on a short timescale.

However, even if they occur at all, real transitions from typical Type 1's to typical Type 2's cannot be regular phenomena on a timescale less than that required to increase the *radio* power of the Type 1 to that of the Type 2, since otherwise many Type 2's with low radio luminosity ($P_{1415\,\mathrm{MHz}} < 10^{21.5}\,\mathrm{WHz}^{-1}\,\mathrm{sterad}^{-1}$, see Fig. 2) would be expected. Note that since many Type 1's have radio luminosities comparable to those typical of Type 2's ($10^{21} < P < 10^{23}\,\mathrm{WHz}^{-1}\,\mathrm{sterad}^{-1}$), no definite statement in the reverse transition can be given. The timescale for an increase of radio power from that of a typical Type 1 to that of a typical Type 2 is hard to estimate. The spatial extent of the radio sources in most classical Seyferts lies in the range a few hundreds of parsecs to a few kiloparsecs (van der Kruit, 1971; de Bruyn and Willis, 1974; Crane, 1977), so, assuming these are representative of Seyfert radio sources in general, a lower limit for this timescale is 10^3–10^4 years. Probably a more realistic estimate may be derived by assuming that the cosmic rays diffuse or are convected with the characteristic velocity of the thermal gas in the forbidden line region, which is typically $10^3\,\mathrm{km\,s}^{-1}$. This approach yields a timescale of 10^5–10^6 years, which is probably also the timescale for significant *decrease* of the radio emission.

The differing distributions of radio luminosity of the two types of Seyferts imply, therefore, that either transitions from Type 1 to Type 2 galaxies do not occur, or, if they do, the timescale for such a transition is in excess of 10^5–10^6 years. This value may be compared with the total duration of the Seyfert phenomenon which, on statistical grounds, must be at least 10^8 years (Woltjer, 1959).

5. Correlations of Radio Luminosity with Optical and Infrared Properties

Because selection effects may lead to spurious apparent relationships in ill-defined samples, only the sample of 41 Seyferts (§ 1) has been used in studying the relation between radio and optical properties. However, in order to reexamine the correlation found by van der Kruit (1971, 1973) and Rieke and Low (1972) between the powers at λ 21 cm and 10 μ, which covered sharp emission line as well as Seyfert galaxies, a much larger sample of objects has been taken. It is also important to note that a spurious correlation may arise in a plot of absolute luminosities in two wavebands if the objects have a small range in apparent brightness but a large range distance. We have, therefore, also made plots involving the two apparent brightnesses to check whether this effect is dominating the corresponding plot of the absolute luminosities. These plots of apparent brightnesses are not presented here but their appearance is described briefly in each case. Because of this effect and the many upper limits in the correlation diagrams, we

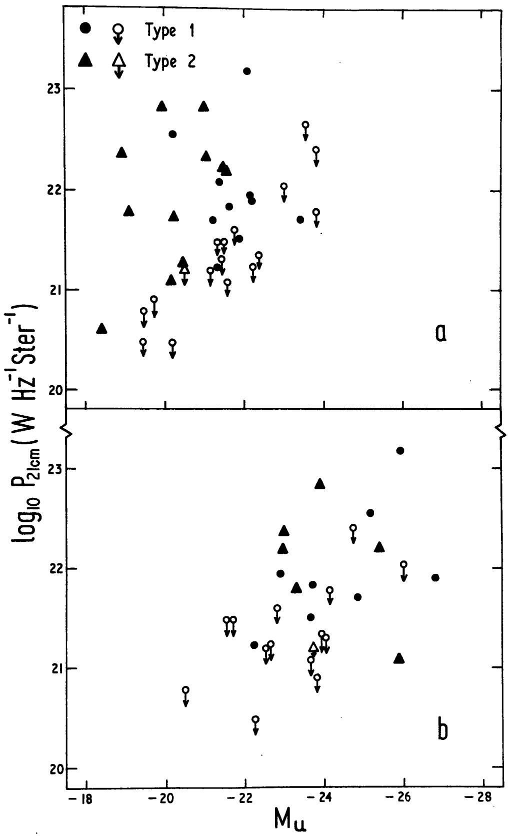

Fig. 3a and b. Relation between the continuum luminosity at λ 21 cm and the absolute magnitude in the U band for galaxies in the sample of 41 defined in § 1. **a** No reddening correction applied to M_U. The 38 galaxies in the sample with measured m_U are plotted. **b** Reddening correction applied to M_U by assuming the Balmer decrement is intrinsically as expected under case B radiative recombination theory (see text). The 29 galaxies in the sample with measured m_U and Balmer decrements are plotted. Note that, for the sake of clarity, detections and upper limits are plotted with different symbols in Figures 3–6

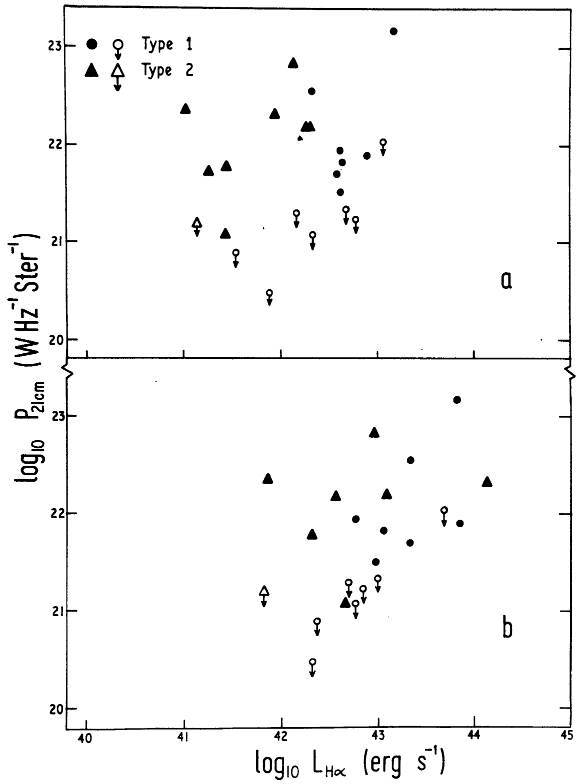

Fig. 4a and b. Relation between the continuum luminosity at λ 21 cm and the luminosity in Hα for galaxies in the sample of 41 defined in § 1, **a** No reddening correction applied to $L_{H\alpha}$. The 23 galaxies in the sample with measured Hα fluxes are plotted. **b** Reddening correction applied to $L_{H\alpha}$ by assuming the Balmer decrement is intrinsically as expected under Case B radiative recombination theory (see text). The 22 galaxies in the sample with measured Hα fluxes and Balmer decrements are plotted

have refrained from applying statistical tests to determine the significance levels of any correlation.

The optical parameters used in correlation studies should, in principle, be corrected for reddening. Unfortunately, the amount of absorption in the nuclei of Seyfert galaxies is still uncertain. A common assumption has been that the intrinsic Balmer decrement is described by Case B conditions and that the steep Balmer decrements observed are a consequence of reddening. However, Stein and Weedman (1976) have recently proposed that the continua of Type 1 Seyfert galaxies are not significantly reddened. Furthermore, Osterbrock (1977) has measured the line intensities in 36 Type 1 Seyferts and concluded that the observed Balmer decrement cannot be accounted for in terms of an intrinsic Case B decrement together with any chosen amount of reddening obeying the Whitford (1958) law. Probably the Balmer decrements in these galaxies are intrinsically steeper than expected on the basis of Case B conditions. On the other hand, it is likely that substantial reddening occurs in the nuclei of most Type 2 Seyferts (e.g., Jones and Stein, 1975; Stein and Weedman, 1976). Because of this uncertainty, in studying the correlation between radio and optical powers ($P_{\lambda 21\,cm}$ vs. M_U, $P_{\lambda 21\,cm}$ vs. $L_{H\alpha}$, $P_{\lambda 21\,cm}$ vs. $L_{[O\,III]\lambda 5007\,Å}$), we have plotted, in each case, two diagrams; in diagram a) the optical parameter has not been corrected for reddening while in diagram b) a correction for reddening has been applied on the assumption that the intrinsic Balmer decrement is described by Case B conditions (Hα/Hβ = 2.8). In all probability, the corrct value lies in between these two extreme cases.

i) $P_{\lambda 21\,cm}$ *vs.* M_U

The nuclei are brighter relative to the galactic disks in U band than in B or V (Adams and Weedman, 1975) so U

is the least contaminated by extranuclear contributions. To study the relation between the radio and optical continua of the nuclei we have, therefore, plotted $P_{\lambda 21\,\mathrm{cm}}$ vs. M_U. Figure 3a shows this relation for 38 out of the 41 galaxies that comprise the aforementioned sample. No *UBV* data are available for Mark 50, 69 and 291. The U magnitudes are from Weedman (1973), Khachikian and Weedman (1974a), Weedman and Khachikian (1969), Dibai (1970) and Braccesi et al. (1968), and were mostly obtained through an aperture 15″ or 17″ in diameter. In Figure 3b, the M_U of the 29 galaxies with measured Balmer decrements (Adams and Weedman, 1975; Osterbrock, 1977; Boksenberg et al., 1977) have been corrected for an absorption $A = 11.21 \log(\mathrm{H}\alpha/2.8\,\mathrm{H}\beta)$ magnitudes. No correlation is apparent in Figure 3a, but a very weak trend may exist in Figure 3b. A plot of $S_{21\,\mathrm{cm}}$ against m_U also shows no correlation if the m_U are as observed and only a weak one if the m_U are corrected for reddening.

ii) $P_{\lambda 21\,\mathrm{cm}}$ vs. $L_{\mathrm{H}\alpha}$

This relation is plotted in Figure 4 using the Hα luminosities given by Adams and Weedman (1975) and Boksenberg et al. (1977). No correlation is apparent unless the values of $L_{\mathrm{H}\alpha}$ are corrected for reddening (Fig. 4b), when a weak trend may exist, analogous to the situation in Figure 3. Segregation by type is, however, apparent in both Figures 4a and b. A plot of $S_{21\,\mathrm{cm}}$ against flux in Hα shows no correlation for fluxes as observed and only a very weak one if the Hα fluxes are corrected for reddening.

iii) $P_{\lambda 21\,\mathrm{cm}}$ vs. $L_{[\mathrm{O\,III}]\,\lambda 5007\,\mathrm{Å}}$

The line [O III] λ5007 Å is the most easily measured of the many forbidden lines found in Seyfert galaxy spectra. As it is well established that in Type 1 galaxies the broad wings on the permitted lines and the much narrower forbidden lines are formed in quite different regions, it is of interest to look for correlations of $P_{\lambda 21\,\mathrm{cm}}$ with $L_{[\mathrm{O\,III}]\,\lambda 5007\,\mathrm{Å}}$ as well as with $L_{\mathrm{H}\alpha}$. In Figure 5a this diagram is plotted for the 22 galaxies in the sample of 41 with measured $L_{[\mathrm{O\,III}]\,\lambda 5007\,\mathrm{Å}}$ (Adams and Weedman, 1975). In Figure 5b, the values of $L_{[\mathrm{O\,III}]\,\lambda 5007\,\mathrm{Å}}$ for the 21 of these galaxies with measured Balmer decrements have been corrected for reddening. A correlation exists in both diagrams, being more prominent in Figure 5b. In part, the correlation reflects the fact that both $P_{\lambda 21\,\mathrm{cm}}$ and $L_{[\mathrm{O\,III}]\,\lambda 5007\,\mathrm{Å}}$ are greater for Type 2 than Type 1 Seyferts. Strong correlations also exist between $S_{\lambda 21\,\mathrm{cm}}$ and the flux in the [O III] λ5007 Å line, whether or not the latter is corrected for reddening. We return to discuss this apparent connection between the continuum radio emission and the forbidden line region later (§ 6.1c).

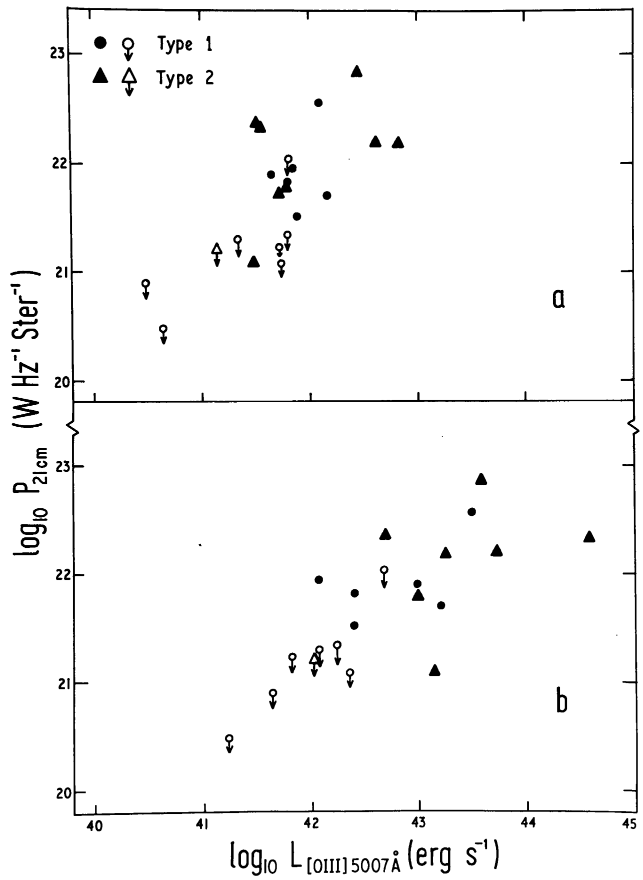

Fig. 5a and b. Relation between the continuum luminosity at λ21 cm and the luminosity in the λ5007 Å line of [O III] for galaxies in the sample of 41 defined in §1. **a** No reddening correction applied to $L_{[\mathrm{O\,III}]\,\lambda 5007\,\mathrm{Å}}$. The 22 galaxies in the sample with measured fluxes in the [O III] λ5007 Å line are plotted. **b** Reddening correction applied to $L_{[\mathrm{O\,III}]\,\lambda 5007\,\mathrm{Å}}$ by assuming the Balmer decrement is intrinsically as expected under Case B radiative recombination theory (see text). The 21 galaxies in the sample with measured [O III] λ5007 Å fluxes and Balmer decrements are plotted

iv) $P_{\lambda 21\,\mathrm{cm}}$ vs. $L_{10\,\mu}$

Van der Kruit (1971, 1973) and Rieke and Low (1972) discovered a rather tight correlation between the luminosities at λ21 cm and 10 μ for about 10 Seyfert galaxies, most of which are the "classical" Seyferts. Several galaxies with *sharp* emission lines (SEL) also appeared to obey this relationship (Rieke and Low, 1972). Figure 6 gives $P_{\lambda 21\,\mathrm{cm}}$ vs. $L_{10\,\mu}$ for nearly four times as many objects, Figure 6a for Type 1 Seyferts and Figure 6b for Type 2 Seyferts and SEL galaxies. Included in this plot are all the galaxies in Tables 4 and 5 of Paper I for which a 10 μ flux density or upper limit is available. Also plotted are NGC 3783, M 82, NGC 253, Mark 52 and NGC 1052 (radio flux densities from Penston et al., 1977; Kellermann and Pauliny-Toth, 1969; Ekers, 1974; Paper I; Wright, 1974, respectively). For the galaxies NGC 3783, IC 4329 A, Mark 266 and Mark 297, the only radio measurement is at λ6 cm. The flux density at

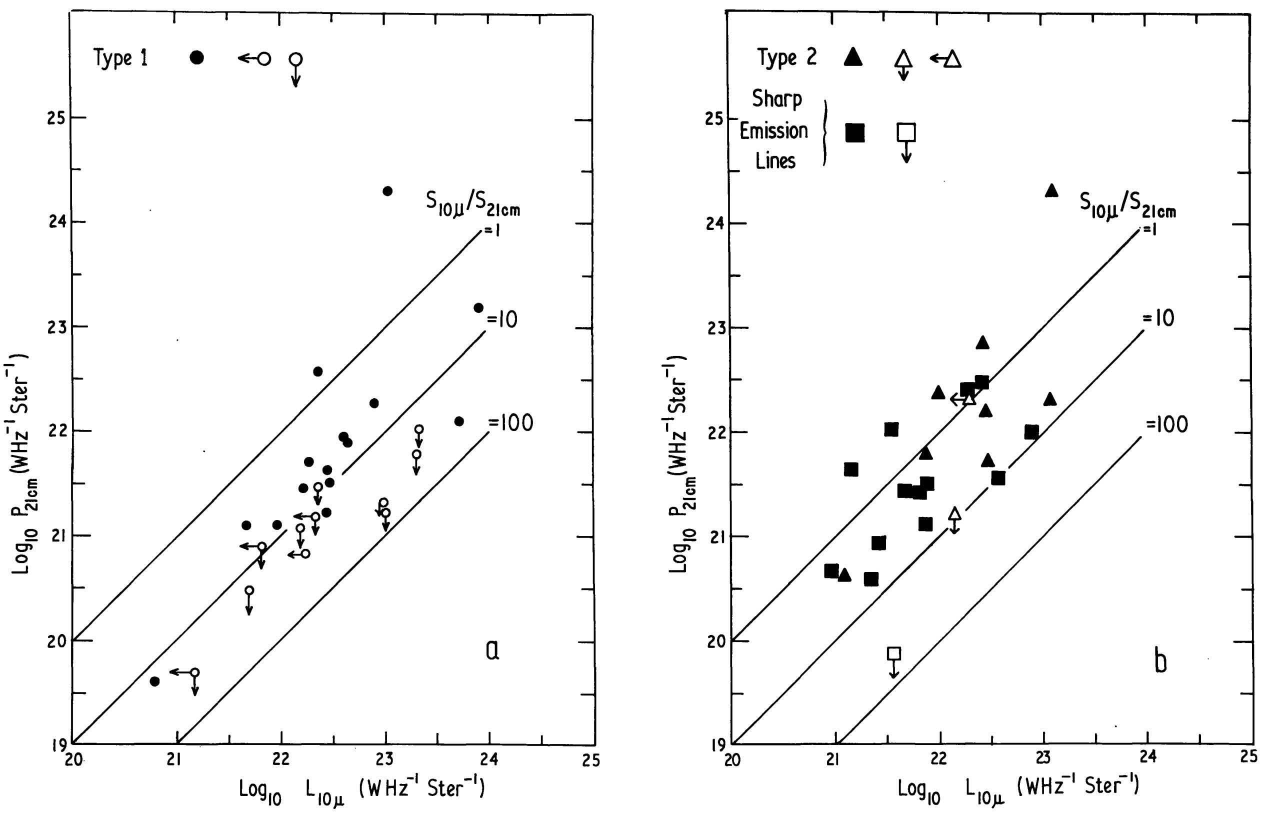

Fig. 6a and b. Relation between the continuum luminosities at λ 21 cm and λ 10 μ for Seyfert and sharp emission line galaxies. **a** Type 1 Seyfert galaxies. **b** Type 2 Seyfert galaxies and sharp emission line galaxies. Lines of constant flux ratio $S_{10\,\mu}/S_{21\,\rm cm}$ are shown. The sample plotted is described in the text

λ 21 cm was, in these cases, derived by assuming the spectral index $\alpha = -0.8$. Data at 10 μ were taken from Rieke and Low (1972), Neugebauer et al. (1976) and Kleinmann and Wright (1974). In addition, galaxies observed by Stein and Weedman (1976) and Allen (1976) at 3.5 μ have been included, after converting their magnitudes at 3.5 μ to flux densities at 10 μ assuming a spectral index $\alpha = -1.25$. This value is the mean spectral index for objects detected at both 3.5 and 10 μ. The errors introduced by this extrapolation are unlikely to exceed a factor of two.

It should be emphasized that neither the Seyfert nor the SEL galaxies plotted in Figures 6a and b form a well defined sample. In particular, the SEL objects were taken from several lists, the only reason for their inclusion being that they appear to follow the relationship of Rieke and Low (1972). Taking all objects together, it is clear that the tight correlation between $P_{\lambda 21\,\rm cm}$ and $L_{10\,\mu}$ that they found does not hold for this increased sample of objects. Several galaxies deviate from the best straight line fit to the detected galaxies by more than a factor of 10 in either radio or infrared luminosity. Also, a plot of flux densities $S_{21\,\rm cm}$ vs. $S_{10\,\mu}$ shows a still significant but weaker correlation, so the relationship apparent in Figure 6 is affected to some extent by the small range of observed values of $S_{10\,\mu}$ and the large range of distances of the objects in the sample.

Before having a closer look at the radio-infrared relation, we wish to point out several reasons for a considerable scatter in it, quite apart from deviations introduced by the inhomogeneity of the sample.

a) Figure 6 compares monochromatic luminosities, but it is now known that there exists considerable dispersion in both the radio and infrared spectral indices (cf. § 3 and, e.g., Neugebauer et al., 1976).

b) The infrared and radio emission often originate in quite different regions and the infrared flux density is aperture-dependent in some cases.

c) The infrared emission of Seyfert and related galaxies is believed to be bimodal in origin; the emission is thermal radiation from dust in NGC 1068, NGC 253 and M82 (Becklin et al., 1973a, b; Jones and Stein, 1975; Rieke and Low, 1975; Gillett et al., 1975) but probably non-thermal in NGC 4151 (Penston et al., 1974) and other Type 1 Seyferts (Stein and Weedman, 1976; Neugebauer et al., 1976).

Figure 6 indicates that, on average, Type 2 Seyferts have a higher radio luminosity for a given infrared luminosity than Type 1 Seyferts. In the ratio of their radio and infrared luminosities, the SEL objects resemble the Type 2 Seyferts. The emission line widths and *UBV* colors of the SEL galaxies are also more like those of Type 2 than Type 1 galaxies. Such continuity of properties between SEL and Seyfert Type 2 galaxies deserves deeper study.

The majority of Type 1 Seyferts (Fig. 6a) fall in a wide band with a width of about a factor of 10 ($S_{10\mu}/S_{21\,\mathrm{cm}}$ ranges from 3 to 30). Although only upper limits are available for the radio and/or infrared luminosity of 11 out of the 26 Type 1 galaxies, only 6 galaxies definitely lie outside this band. Two of those 6, 3C 120 and Mark 6, lie in the top left part of the diagram. It is not surprising that these two objects are anomalous, for 3C 120 is a very compact and variable radio source with complex structure, while the uncertain type of Mark 6 has already been noted. The other 4 galaxies, IZw1, Mark 9, 304 and 335, fall in the lower-right part of the diagram and thus have anomalously high values of $S_{10\mu}/S_{21\,\mathrm{cm}}$. Despite these discrepancies, the loose correlation of Figure 6a for the Type 1 galaxies is of considerable interest in view of the non-thermal origin of both radio and infrared continua and is further discussed in § 6.3.

v) $P_{\lambda 21\,\mathrm{cm}}$ vs. Optical Morphology

Recently, Adams (1977) has published an extensive morphological study of Seyfert galaxies. Although many galaxies defy an unambiguous classification, it appears that about 50% of the galaxies in the sample of 41 show indications of spiral structure. Among the remaining objects, there are very compact, nearly stellar objects, elliptical galaxies and galaxies with distorted structure, jets or filaments. The 21 galaxies in this sample which are detected at λ 21 cm show no statistically significant association with any of these morphological groups. There is a suggestion that the very compact or quasi-stellar objects are not strong radio sources, although this is probably a selection effect since they also tend to be the most distant. On the other hand, the majority of the galaxies with peculiarities in their optical structure are radio emitters (Markarian 6, 110, 231, 273, 298).

6. Nature of the Non-thermal Sources in Seyfert Galaxies

6.1. Spatial Extent of the Radio Source and the Correlation between Radio Continuum and Forbidden Line Emission

A discussion on the nature of the non-thermal radio emission in Seyfert galaxies depends rather critically on the dimensions of the radio sources. For most of the objects in the sample under investigation we have only upper limits on the size of the radio emitting region. However, many of the nearby classical Seyferts have been resolved and if they are representative, the emitting region must typically be of the order of several hundred pc to a few kpc in diameter (van der Kruit, 1971; de Bruyn and Willis, 1974; Crane, 1977). This is interestingly close to the dimensions of the forbidden line region (FLR) in models of the structure of Seyfert galaxies (e.g., Osterbrock, 1971). The FLR has also been resolved at the telescope in a number of nearby Seyferts (NGC 1068, Walker, 1968a; NGC 4151, Walker, 1968b; NGC 7469, Ulrich, 1972) and found to have a size of the order of 1 kpc. We now discuss a physical situation in which this agreement in size between FLR and radio source and the correlation of Figure 5 find a natural explanation. If the λ 21 cm radiation and the [O III] λ 5007 Å line originate in the same overall volume of space, one would expect to see a correlation between the intensity of these two quantities if the condensations emitting the forbidden line radiation are always in pressure equilibrium with the enveloping cosmic rays and magnetic fields responsible for the radio emission. An exactly analogous pressure balance occurs in the Crab Nebula, where it is believed that the cosmic rays and magnetic field play a vital role in confining the line emitting filaments (Woltjer, 1958). Writing V_{radio} and V_{thermal} as the volumes occupied by the radio emitting and thermal gases respectively, the radio power $P_{\lambda 21\,\mathrm{cm}} \propto n_{\mathrm{cr}} B^{(\gamma+1)/2} V_{\mathrm{radio}} \propto B^{(\gamma+5)/2} V_{\mathrm{radio}}$ (for equipartition between cosmic rays and magnetic field) $\propto B^{3.75}$ for the typical $\gamma = 2.5$. The luminosity of the collisionally excited [O III] λ 5007 Å line radiation will be $L_{[\mathrm{O\,III}]\lambda 5007\,\mathrm{Å}} \propto n_e n_i V_{\mathrm{thermal}}$, where n_i is the density of O^{++} ions, as long as collisional deexcitation is unimportant (the critical electron density for collisional deexcitation of the $^1D_2$ level of [O III] is $n_c = 6.5\,10^5\,\mathrm{cm}^{-3}$, see Osterbrock, 1974, p. 53). The relative of n_i and n_e is dependent upon details of the ionization equilibrium; if, however, $n_i \propto n_e$ then $L_{[\mathrm{O\,III}]\lambda 5007\,\mathrm{Å}} \propto n_e^2 V_{\mathrm{thermal}} \propto B^4 V_{\mathrm{thermal}}$ for pressure balance $n_e k T_e = B^2/4\pi$ and $T_e = \mathrm{constant}$. Thus we expect $P_{\lambda 21\,\mathrm{cm}} \propto (L_{[\mathrm{O\,III}]\lambda 5007\,\mathrm{Å}})^{1.07}$ if variations in n_e (and hence B) are the dominant cause of differences in $L_{[\mathrm{O\,III}]\lambda 5007\,\mathrm{Å}}$ and $P_{\lambda 21\,\mathrm{cm}}$ between different galaxies. If, on the other hand, different galaxies have similar values of n_e and B, but differing V_{radio} and V_{thermal}, $P_{\lambda 21\,\mathrm{cm}} \propto L_{[\mathrm{O\,III}]\lambda 5007\,\mathrm{Å}}$ as long as $V_{\mathrm{radio}} \propto V_{\mathrm{thermal}}$. Thus, under these approximations, we expect $P_{\lambda 5007\,\mathrm{Å}} \propto L_{[\mathrm{O\,III}]\lambda 5007\,\mathrm{Å}}$ which is consistent with Figure 5.

From the radio properties of a typical Seyfert galaxy—$P_{\lambda 21\,\mathrm{cm}} = 10^{22}\,\mathrm{W\,Hz^{-1}\,sterad^{-1}}$, radius 500 pc, volume filling factor $= 1$ (assumed), spectral index $\alpha = -0.75$, low frequency cut-off 10 MHz and equal energy in relativistic electrons and protons—we deduce an equipartition magnetic field $B = 1\,10^{-4}$ Gauss. If the thermal condensations have a temperature of 10^4 K, an electron density $n_e \simeq 500\,\mathrm{cm}^{-3}$ will yield pressure equilibrium between relativistic plasma and thermal condensations. This is a typical value for the electron density in the FLR as deduced from *optical spectroscopic* studies.

On this picture, galaxies strong in both λ 21 cm continuum radiation and in the [O III] λ 5007 Å line have a well developed FLR, either because the value of n_e is higher, or because the emitting volume is larger. Whatever the details, a prediction is that $P_{\lambda 21\,\mathrm{cm}}$ should also be proportional to the luminosity of the *cores* of the Balmer lines in Type 1 galaxies, since these are believed to originate in the same region as the forbidden lines. If variations in n_e are the dominant cause of differences in $L_{[\mathrm{O\,III}]\lambda 5007\,\mathrm{Å}}$ from galaxy to galaxy, a correlation between n_e (as could be derived, for example, from the intensity ratio of the [S II] lines at $\lambda\lambda$ 6717, 6731 Å) and $P_{\lambda 21\,\mathrm{cm}}$ would be expected. Spectrophotometric measurements of a large number of Seyfert galaxies are required to check these predictions.

6.2. Spatial Extent of the Infrared Source in Type 1 Seyferts

It has recently been argued (Stein and Weedman, 1976; Neugebauer et al., 1976) that the infrared and optical continuum radiation from Type 1 Seyfert galaxies is non-thermal in origin. An estimate of the size of this infrared source may be obtained from the intensity variations seen in a few objects (Penston et al., 1974 and references therein). These variations have been observed on time scales as short as a few months and the source size can, therefore, be not greater than about 0.1 pc. A second argument that can be used to set limits on the size of the infrared sources goes as follows. As is well known, the spectrum of synchrotron radiation cannot rise toward higher frequencies faster than $\nu^{1/3}$ in the absence of absorption. However, examination of Figure 6 shows that for 2 galaxies $S_{10\,\mu}/S_{21\,\mathrm{cm}}>27.8$ which implies the two point spectral index $\alpha_{21\,\mathrm{cm}-10\,\mu}>0.33$. In the cases of another 2 galaxies, for which the flux is known at 3.5 µ but not at 10 µ, $\alpha_{22\,\mathrm{cm}-10\,\mu}>0.33$ if $\alpha_{10\,\mu-3.5\,\mu}\leqq -1.25$. For 10 Type 1 galaxies in Figure 6, only upper limits to $S_{21\,\mathrm{cm}}$ are available; it seems likely that more sensitive radio surveys will show that for at least some of these galaxies as well, $\alpha_{21\,\mathrm{cm}-10\,\mu}>0.33$. Future measurements of the radio flux at shorter wavelengths than λ 21 cm and the infrared at longer than 10 µ will also be of value in determining how sharply the spectrum must decrease from the infrared to the radio.

For some galaxies at least, therefore, the infrared spectrum, assumed synchrotron in origin, *must* suffer absorption at wavelengths in excess of 10 µ. We consider two possible absorption processes for each of which stringent upper limit on the size of the infrared source is implied.

i) Synchrotron Self-absorption. If synchrotron self-absorption is relevant, the characteristic turn-over frequency $\nu_{\max}$ must obey

$$\nu_{\max}>\{2.04\,10^{24}(3\,10^{13})^{-\alpha_{ir}}\}^{1/(2.5-\alpha_{ir})} \quad (1)$$

for those sources with $S_{21\,\mathrm{cm}}/S_{10\,\mu}>27.8$, since the spectral index in the optically thick regime cannot exceed 2.5. In Equation (1) α_{ir} represents the spectral index between $\nu=\nu_{\max}$ and $\nu=3\,10^{13}$ Hz (i.e., $\lambda=10\,\mu$). Taking $\alpha_{ir}=-1.25$, which is the mean spectral index between 10 µ and 3.5 µ, $\nu_{\max}>9.4\,10^{10}$ Hz. The power at 10 µ is generally in the range 10^{21}–10^{23} WHz^{-1} sterad^{-1} (see Fig. 6), so $P_{\nu_{\max}}<10^{24}$–10^{26} WHz^{-1} sterad^{-1}, where we have again taken $\alpha_{ir}=-1.25$. For a uniform synchrotron source of linear size d(pc), magnetic field B (Gauss), the turnover frequency ν_{nax} (MHz) is given by

$$\nu_{\max}=3.1\,10^{-6}\left(\frac{P_{\nu_{\max}}}{d^2}\right)^{2/5} B^{1/5}. \quad (2)$$

With the above values of $P_{\nu_{\max}}$ and $\nu_{\max}$, Equation (2) implies $d<(0.08$–$0.8)\,B^{1/4}$ pc. The magnetic field in this region emitting the infrared continuum is not known; plausible values in the range 10^{-2}–1 Gauss imply upper limits on the size $d<0.025$ pc to $d<0.8$ pc. Since we have taken ν_{nax} to be as low as possible, these upper limits on d may well be conservative by a factor of 100 or more.

ii) Free-free Absorption. If the rapid decrease of flux from infrared to radio wavelengths is a consequence of free-free absorption by a thermal gas, the size of the infrared source must also be very small, since the only nuclear component capable of free-free absorption at such short wavelengths is the dense gas which emits the broad wings on the Balmer lines. The scale of this component is ~0.01 pc so the infrared continuum source must be of comparable or smaller extent.

From these arguments, it may be concluded that the typical size of the source radiating the non-thermal *infrared* continuum in Type 1 Seyferts is certainly less than 1 pc and very probably less than 0.01 pc. This value should be compared with the scales of hundreds of parsecs to a few kiloparsecs appropriate to the non-thermal *radio* emission (§ 6.1.).

6.3. The Relation between the Radio and Infrared Continuum Powers

The probable correlation between the continuum powers of Type 1 Seyferts at λ 21 cm and λ 10 µ (see Fig. 6a) implies a relation between the two populations of relativistic electrons. As shown in the two previous subsections, however, these populations occupy quite different volumes of space. The simplest hypothesis interrelating the two populations is that relativistic electrons from the same injection spectrum cause the emission in the two wavebands. The fact that at least 10% of the Seyfert galaxies have a compact ($\lesssim 1$ pc) radio core lends support to a picture in which electrons, that later radiate in the more extended radio region, are accelerated near or in the core. However, the following two conditions then have to be met: i) The core electrons must stream outward at relativistic velocities. If the relativistic electrons diffuse or convect away from the central source at speeds characteristic of the velocity dispersion of the thermal gas (i.e., 10^3–10^4 km s^{-1}) they lose almost all their energy to inverse Compton scattering off the optical and infrared continuum photons before they have propagated more than a few parsecs (see Appendix). ii) The energy spectrum of the relativistic electrons must be curved with the break (from $\gamma \approx 2.5$ to $\gamma \approx 3.5$) at energies around a few GeV. Electrons with energies below this break radiate at radio frequencies in a magnetic field of about 10^{-4} Gauss (§ 6.1.) while those with energies above it radiate in the infrared and optical regime in a field of about 1 Gauss. The break in the energy spectrum could be an intrinsic feature of the injection spectrum but it may also be the result of a particular combination of radiative losses and propagation mode. It is well known that synchrotron and inverse Compton losses steepen the spectrum of relativistic electrons because of the E^2-dependence. On the other hand, ionization losses have virtually no dependence on energy and result in a flattening of the spectrum (e.g., Pacholczyk, 1970, p. 143 ff). The latter losses can be very severe in the high density nuclei of Seyfert galaxies and may dominate the radiative losses up to energies of 1 GeV. We have, however, insufficient knowledge of the density structure of the nuclei to settle this argument at present.

One of the predictions of a model in which the "radio-electrons" are accelerated in the core is that Type 1 Seyferts should be stronger X-ray sources than Type 2 Seyferts because the ambient photon energy density—which determines the inverse Compton X-ray production for an equal number of "radio-electrons"—is much higher in the inner 0.1–1 pc of Type 1 Seyferts. [The dominant contribution to this photon energy density in the inner region comes from the non-thermal continuum which is strong in Type 1 Seyfert nuclei but weak or non-existent in Type 2 Seyfert nuclei (cf. Neugebauer et al., 1976).] Such a difference in X-ray power is, indeed, observed (Elvis et al., 1977). Conversely, since the energy drain on the relativistic electrons due to inverse Compton scattering is smaller in the Type 2's, their stronger radio emission (§ 4) may be accounted for.

If condition (i) is not met and the relativistic electrons do not stream away from the infrared/optical continuum source at relativistic velocities, they must be accelerated at distances in excess of a few parsecs from it. Perhaps such acceleration could be ascribed to the high velocity gas responsible for the forbidden emission lines via the often invoked process of particle acceleration via plasma turbulence. The relation between the radio and infrared powers would then arise if the amplitude of these turbulent motions were somehow correlated with the infrared continuum power. Such a situation might arise in models of the type described by Kippenhahn et al. (1975) and Mestel et al. (1976) in which the line emitting gases are accelerated by the optical/infrared radiation fields.

Although the above discussion of the relation between the radio and infrared powers has centered on Type 1 Seyferts, some loose correlation may exist for Type 2's and SEL galaxies as well (see Fig. 6b). In contrast to the situation in Type 1 galaxies (§ 6.2.), recent discussions of the origin of infrared radiation in Type 2 Seyferts (Jones and Stein, 1975; Neugebauer et al., 1976) have favoured an interpretation of the 10 μ flux as thermal radiation from dust. No simple physical relation between such radiation and the non-thermal radio emission comes to mind. However, the dust could be heated by a central, possibly non-thermal optical/ultraviolet source (Jones and Stein, 1975) which may also be the ultimate source of energy for the radio emitting electrons, as we have already discussed for Type 1 galaxies. Indirect schemes such as this seem capable, at least in principle, of accounting for the loose relation apparent in Figure 6b.

7. Seyfert Galaxies and Quasi-stellar Objects

The continuity in properties between Type 1 Seyfert galaxies and QSO's has often been mentioned in the literature [for some recent discussions, see Weedman (1976) and Rowan-Robinson (1977)]. The strongest arguments for the existence of such a continuity are the similarities in their optical spectroscopic properties and the smooth joining of their optical luminosity functions around $M_V \sim -23$ (Sargent, 1972; Notni and Richter, 1972; Huchra and Sargent, 1973). It is, at present, unclear to what extent the radio properties of Seyfert galaxies and QSO's share in this continuity. A number of radio-selected, radio-loud Seyfert galaxies (e.g., 3C 382, 3C 390.3) exhibit the double structure characteristic of many of the radio-selected, radio-loud quasi-stellar objects in the 3CR catalogue. Such radio-loud objects, however, comprise only a small fraction of Seyferts and QSO's. Most Type 1 Seyferts are, as discussed in the present work, radio-faint, being detectable as weak radio sources associated with the nucleus of the galaxy. Such galaxies are presumably analogous to the radio-quiet QSO's. Radio surveys of Seyfert galaxies and QSO's down to flux density levels $\lesssim 0.1$ mJy will soon be feasible and, judging by the results of Paper I, we may expect many of the Type 1 Seyferts and some of the radio-quiet QSO's to be detectable at this level. Only with the results of such a survey could the radio properties of Type 1 Seyferts and QSO's be profitably compared.

8. Conclusions and Future Work

Our study shows that Seyfert galaxies typically exhibit a nuclear radio source with a steep spectrum ($-0.5 < \alpha < -1.0$, § 3), a power at $\lambda 21$ cm $P_{\lambda 21\,\mathrm{cm}}$;$10^{21}-10^{22}$ W Hz^{-1} sterad^{-1} (§ 4) and a spatial extent of several hundreds of parsecs to a few kiloparsecs (§ 6). (However, $\gtrsim 10\%$ of Seyferts have a flat spectrum, very compact radio source and a few others possess a halo with size several tens of kpc.) The region of space occupied by the typical radio source is thus quite similar to that of the forbidden line region. To account for the correlation of radio power with Seyfert type (§ 4) and with the luminosity in the [O III] λ 5007 Å line (§ 5), it is suggested that the cosmic rays and magnetic field responsible for the radio emission may be in pressure equilibrium with the condensations of gas radiating the forbidden lines. This scenario resembles the situation found in the Crab Nebula where cosmic rays and a magnetic field of strength $\sim 10^{-4}$ Gauss are in rough pressure balance with the line emitting filaments ($T_e \sim 10^4$ K, $n_e \sim 10^3$ cm^{-3}). Predictions of this idea are that the radio power from Seyferts should be correlated with the power in the *cores* of the Balmer lines and/or with the electron density in the forbidden line region.

The relativistic electrons radiating centimetre radio emission are subject to severe losses to inverse Compton scattering if they originate in the small (<0.1 pc) core source, which is believed to radiate the optical and infrared continua in Type 1 galaxies. In fact, the "radio" electrons radiating at several hundreds of parsecs from this source cannot have originated in it and then diffused or convected away from it at speeds characteristic of the thermal gas. The electrons must either stream outward from the core relativistically or be accelerated "in-situ", perhaps by turbulent motions of the gas radiating the forbidden lines.

Current observational work at radio wavelengths, aimed at confirming and extending these ideas, includes:

a) A deeper survey of the undetected (mainly Type 1) galaxies in the sample of 41 to reduce the large number of upper limits on their flux density. Such a clarification of the radio luminosities of Type 1 galaxies is desirable for deeper study of the correlations of radio with infrared and optical properties, to decide whether absorption of the infrared spectrum at $\lambda > 10\,\mu$ is a common feature of Seyfert galaxies, and to compare with the radio properties of QSO's.

b) Observation of the ~40 Seyfert galaxies not observed in the survey described in Paper I.

c) Higher resolution studies of detected galaxies to check the conclusion that the radio source is, in general, several hundreds of parsecs to a few kiloparsecs in extent.

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Appendix

Energy Losses of Relativistic Electrons Propagating Outwards from the Small Infra-red/optical Continuum Source

Although it is likely that synchrotron and ionization losses play a role in reducing the energy of the relativistic electrons, particularly at large distances from the continuum source, their magnitude is hard to estimate reliably. We include, therefore, only losses due to inverse Compton scattering and show that even this process represents a catastrophic drain on the particle energies.

The rate of energy loss dE/dt of the relativistic electrons due to inverse Compton scattering is given by:

$$dE/dt = -4\,10^{-2} f \omega_{\rm rad} E(r)^2 \quad \text{(c.g.s. units)} \tag{A1}$$

where f is a factor which takes into account deviations from isotropy in the angular distribution of the photon field seen by the electron ($f=1$ for an isotropic distribution) and $\omega_{\rm rad}$ is the energy density of the radiation field [$\omega_{\rm rad} = 10^{44} L_{44}/4\pi r^2 c$, where L_{44} is the luminosity (erg s^{-1}) of the assumed pointlike, optical/infra-red continuum source and r is the distance from it]. Writing $dt = dr/v$ where v is the bulk velocity of the relativistic electrons radially outwards, we obtain

$$dE/dr = -1.1\,10^{31} f L_{44} E^2(r)/r^2 v\,. \tag{A2}$$

Integrating this equation with $E=E_1$, at $r=r_1$, and $E=E_2$ at $r=r_2$ ($E_1>E_2$, $r_2>r_1$) yields

$$(E_1^{-1} - E_2^{-1}) = 1.1\,10^{31} f L_{44}(r_2^{-1} - r_1^{-1})/v\,. \tag{A3}$$

We envisage that the electrons are injected at $r_1 \leqq 0.1$ pc. To radiate at 1.4 GHz in a field $B=10^{-4}$ Gauss at $r_2 \gtrsim 100$ pc (Section 6.1), $E_2 = 1.8\,10^{-3}$ erg is required. Taking $E_1 \gg E_2$, Equation (A3) yields

$$v > 6\,10^{10} f L_{44}\ \text{cm s}^{-1}\,. \tag{A4}$$

Equation (A4) implies that it is not possible for the radio electrons to survive the journey from the core (<0.1 pc) to large radii if $L_{44} \sim 1$, unless they move outwards at relativistic velocities. For radial motion at relativistic speeds $f \ll 1$, since the inverse Compton losses are reduced by the factor $\sin^4(\theta/2)$, where θ is the angle between the particle and photon trajectories (e.g. Woltjer, 1966).

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