PHYSICAL CONDITIONS IN RADIO GALAXIES AND QUASARS*

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It is well known from the pioneering work of Baade and Minkowski that radio galaxies very often have strong emission lines in the spectra of their nuclei, indicating the presence of relatively large amounts of ionized gas. For instance, in the early survey of radio galaxies by Schmidt (1965), of the 35 galaxies observed, 32 had at least [O II] λ3727 in their spectra and well over half had relatively strong [O II] and other observable emission lines as well. In the recent review of optical identifications and spectroscopy of the revised 3C catalogue of radio sources by Smith et al. (1976), 137 radio galaxies are listed. Of these descriptive spectral information is given for 98, of which 49 show strong-emission line spectra, 19 intermediate-strength emission, 12 weak emission, and 18 a pure absorption-line spectrum without detectable emission lines. The fraction of objects with emission line-spectra is much higher than for normal galaxies. It is thus apparent that though the presence of emission lines is neither a necessary nor a sufficient condition that a galaxy be an observable radio source, nevertheless a large fraction of radio galaxies do contain ionized gas in their nuclei.

For the past several years, therefore, a group of us at Lick Observatory have been using the image-tube scanner (Robinson and Wampler 1972, 1973; Miller et al. 1976) with the 3 m telescope for a spectrophotometric survey of radio galaxies and related objects. The aim is to use the well-known techniques of analyzing gaseous nebulae from measurements of their emission-line spectra to try to understand the physical conditions in the ionized gas in the nuclei of radio galaxies and ultimately the energy source, energy-input mechanism and basic nature of the radio-galaxy phenomenon (or phenomena).

First let us discuss Cyg A = 3C 405, one of the brightest radio sources in the sky, known from the work of Baade and Minkowski (1954) to have very strong emission lines. Our spectrophotometric study of this galaxy has already been published (Osterbrock and Miller 1975).

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In form Cyg A is a not untypical cD galaxy with a double nucleus. Possibly the double nucleus is the apparent result of the presence of a dust lane similar to that in the much nearer radio galaxy Cen A, for a direct photograph of Cen A taken with a short focal-length telescope appears very similar to the large-telescope direct plate of Cyg A.

We were able to measure the relative intensities of 24 emission lines in the spectrum of Cyg A and in addition to set upper limits to the strengths of 4 other important lines. A wide range in ionization is observed, from [O I], [N I] and [S II], through strong [O III], [N II] and [Ne III] to [Ne V], [Fe VII] and [Fe X]. The emission lines all have similar profiles, with full widths at half maximum of approximately 500 km s^{-1}. The H I Balmer lines have a very steep gradient which can be attributed to interstellar extinction, part of which must occur in Cyg A. The amount of extinction derived in this way corresponds to $E_{B-V} = 0.7$ magnitudes, and was used to correct the observed line intensities not only of the H I lines but of the other recombination and collisionally excited lines. The wide range of observed lines indicates a wide range of ionization in the nucleus of Cyg A. The [O III] ratio implies a mean temperature of approximately 15000° in the O^{++} region while the [N II] ratio implies a mean temperature approximately 10000° in the N^{+} emission region. Furthermore, these ratios indicate that the electron densities $N_e < 10^6$ cm^{-3} in the ionized regions. The [S II] ratio indicates $N_e \approx 10^3$ cm^{-3} in the S^{+} region. None of these parameters are strikingly dissimilar from the physical conditions in a typical high-surface brightness planetary nebula. Furthermore, the relative strengths of the lines indicate that the abundances of the light elements are similar to the abundances in planetary nebulae or H II regions of our Galaxy.

The continuous spectrum of Cyg A shows no detectable absorption lines. The observed continuum approximately fits the power law $F_\nu \propto \nu^{-n}$ with n = 3.3,or if the correction for extinction derived from the observed emission lines is applied, n = 1.6.

The mass of ionized gas in Cyg A may be estimated from the observed H I line flux. The luminosity $L(H\beta) \approx 2 \times 10^{42}$ ergs s^{-1} with the distance 3.4×10^8 pc derived from the observed redshift. If we assume the mean electron density in the ionized gas $N_e = 10^3$ cm^{-3}, the mass of ionized gas is approximately 2×10^7 $M_\odot$. The derived mass is inversely proportional to the assumed density. With $N_e = 10^3$ cm^{-3}, the ionized volume corresponds to a sphere with radius 100 pc or approximately 0.1 at the distance of Cyg A, far smaller than the observed bright central region which is several seconds in diameter. Clearly in Cyg A as in many other emission-line galaxies the ionized gas has a highly non-uniform distribution within the observed volume or, in other words, the filling factor is quite small.

The wide range of ionization observed in the emission-line spectrum of Cyg A must give some information on the energy-input mechanism. One possible energy-input mechanism, the conversion of kinetic energy

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to heat (shock-wave heating) can be eliminated, because of the weakness of [O III] 4363 and the resulting low calculated mean temperature in the O^{++} region mentioned above. Therefore a plausible working hypothesis is that the energy-input mechanism is photoionization as in planetary nebulae and H II regions, though hot stars can be ruled out as the source, because models as well as observations show that their radiation cannot produce the wide range of ionization observed in radio galaxies. However, photoionization by a power-law spectrum or other spectrum extending far to the ultraviolet may produce the observed emission lines. The observed Cyg A line intensities corrected for interstellar extinction agree reasonably well with a photoionization model calculated by McAlpine (1971) for a power-law input spectrum from an assumed central source with n = 1.2, not too different from the index derived for the optical continuum of Cyg A, n = 1.6. This model assumes $N_e = 10^4$ cm^{-3}, a filling factor $\epsilon = 0.01$ and a corrected helium abundance N(He)/N(H) = 0.09. The observed Cyg A line spectrum agrees even better with the observed spectrum of NGC 1952, which is known to be photoionized by a synchrotron source, except that in it all the He lines are stronger as the result of an abundance effect. Thus at present it is plausible to suppose that the Cyg A emission lines arise in a gas with relatively normal abundances ionized by a central synchrotron power-law source. Other possible sources, for instance a hot, massive superstar, are not excluded; if the ultraviolet fluxes expected from such sources can be calculated, they should be used as the input spectra for photoionization models to be compared with Cyg A.

Of the radio galaxies observed in our spectrophotometric survey at Lick to date, approximately 2/3 have narrow emission lines with widths similar to the emission lines in Cyg A, approximately 500 km s^{-1}. The narrow-line radio galaxies reduced and discussed by our group to date include 3C 98, 3C 178, 3C 192, 3C 327 and PKS 2322-12 by Costero and myself (1976) and 3C 33, 3C 184.1, 3C 433, 3C 452 and 5C 3.100 by Koski (1976). Most of these galaxies have emission-line spectra similar to that of Cyg A, though weaker (by different amounts) with respect to the continuous spectrum. Two of them, 3C 178 and PKS 2322-12, have a somewhat lower general level of ionization, with [O III] λ5007 comparable in strength to Hβ, and [Ne V] and [Fe VII] emission undetectable. In all these galaxies, in contrast to Cyg A, absorption lines of an integrated stellar spectrum can be seen. These lines are weaker than in normal galaxies without emission lines, probably indicating that the observed continuum is a combination of a galaxy spectrum with a featureless power-law or synchrotron continuum of the Cyg A type. In several of the narrow-line radio galaxy spectra, H I absorption lines can be seen in the near ultraviolet, indicating the presence of early-type stars. These features do not occur in all narrow-line radio galaxies, however; in some the absorption-line spectrum is a good match to a normal elliptical gallaxy.

The spectra of the narrow-line radio galaxies may be approximately corrected for interstellar extinction on the assumption that the H I

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lines arise by recombination. The calculated amounts of extinction are large, ranging from $E_{B-V} = 0.3$ for 3C 192 to about $E_{B-V} = 1.1$ for 3C 178. These same extinctions would give corrected continuous spectra much bluer than observed in normal elliptical galaxies, suggesting that the gas and dust are closely associated in a small volume in the radio galaxies, and that the stellar population occupies a larger volume and does not suffer the full extinction (Warner 1973).

The emission-line spectra of all these radio galaxies have [O III] line ratios corresponding to $N_e = 10^4$ to 10^6 cm^{-3}, if $T \approx 10000°$, and thus give no evidence for shock-wave heating. It seems likely that the objects with emission-line spectra similar to Cyg A can also be reasonably well fitted by photoionization models with power-law input spectra. The low-ionization objects have spectra similar to the nuclei of the spiral galaxies M 51 and M 81 (Peimbert 1968, 1971) though the [O I] and [S II] lines are not quite as strong in these latter objects. The emission lines are also significantly narrower in the two spiral galaxies than in the two radio galaxies. The input mechanism is not known in either case. Photoionization models with a steeper power law, such as $F_\nu \propto \nu^{-2}$ or ν^{-3} should be calculated to see if they will reproduce the combination of strong [O I] and [S II] dependent on a large partly ionized region, with fairly weak [O III] indicating a relatively low general level of ionization.

In addition to radio galaxies, we have also been observing the spectra of Seyfert galaxies, which appear in many ways to be closely related objects. In the classification scheme of Khachikian and Weedman (1971, 1974), the analogues to narrow-line radio galaxies are Seyfert 2 galaxies. To date, Koski has reduced and discussed the spectra of 19 of these objects. Most of them have emission-line and continuous spectra indistinguishable from the spectra of narrow-line radio galaxies, and it thus appears that the ionized gas nuclei of these two classes of objects are very similar physically.

About 1/3 of the emission-line radio galaxies we have observed have, in contrast to the narrow line-radio galaxies, relatively broad (10000 km s^{-1} or more) H I emission lines and narrow forbidden lines similar to those in narrow-line radio galaxies. These objects include 3C 227, 3C 382, 3C 390.3, 3C 445 (Osterbrock, Koski and Phillips 1975, 1976) and 3C 120 (Phillips and Osterbrock 1975). Several of them had previously been reported to have broad or double emission lines by Lynds and Burbidge. In all these broad line-radio galaxies except 3C 120 the H I emission lines have weak narrow components with the same widths and redshifts as the forbidden lines, and the broad components have irregular nonsymmetric profiles. In each of these four radio galaxies the H I emission lines have different and unusually steep decrements. Broad weak He I and He II emission features are detectable in some of these galaxies. Variations in the H I line profiles of 3C 390.3 were clearly observed between 1974 and 1975. The narrow emission lines in all these galaxies have relative intensities

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approximately the same as in Cyg A, but [O II] λ3727 is weaker and [O III] λ4363 is significantly stronger in the narrow-line spectra of the broad-line radio galaxies. This probably indicates electron densities $N_e \approx 10^6$ to 10^7 cm^{-3} in their O^{++} zones.

In the broad-line region on the other hand N_e must be quite high, as shown by the complete absence of any forbidden lines, which must be due to collisional de-excitation. So far as I know, this interpretation was first published in the context of Seyfert galaxies by Woltjer (1968). Quantitatively it appears that $N_e \gtrsim 10^8$ cm^{-3} in the broad-line region. The mechanism responsible for emission of the broad H I emission is clearly of great interest. The fact that the continuous spectra of all four galaxies show only weak stellar absorption lines, and approximately follow power-law forms suggest that they all have strong nonthermal contributions. Furthermore the total equivalent widths of Hβ emission in all four galaxies are roughly the same, suggesting that photoionization followed by recombination has something to do with the excitation. However, the measured Balmer decrements do not follow the recombination gradient for any assumed interstellar extinction, nor are the measured Balmer decrements the same in all four galaxies, so the excitation is certainly not due to recombination alone. Probably collisional excitation and Balmer-line self-absorption, both strongly modify the H I emission. Some calculations of these effects have been made by Shields (1974), Adams and Petrosian (1974) and Netzer (1975), but further theoretical work using accurate collision cross-sections and modelling the strong density fluctuations that must occur is clearly necessary.

The total amount of gas in the broad-line region is not very large, of order 10 $M_\odot$ and the radii of the ionized regions deduced assuming $\epsilon = 1$ are quite small of order 0.01 pc. It is therefore easy to understand the time variation of the H I profile in 3C 390.3. The broad irregular profile of the H I lines must result from mass motions of the ionized gas in a relatively small number of clouds or streams. There is a good correlation between line width and Hβ luminosity in these four radio galaxies.

The emission-line spectra of the broad line radio galaxies are similar in many ways to those of Seyfert 1 galaxies, and we have therefore also been observing these objects. To date the spectra of 35 Seyfert 1 galaxies have been reduced and discussed (Osterbrock 1976). None of these Seyfert galaxies has H I emission line widths as great as in the two broad-line radio galaxies with the widest lines, 3C 382 and 3C 390.3, though they cover the range of the other three radio galaxies, and one of these, 3C 120, was first discovered as a Seyfert galaxy (Arp 1968) and is often so described. Most of the measured line ratios of the Seyfert 1 galaxies cover the range within which the broad-line radio galaxies fall, though there are a few differences that appear observationally significant. One is that the Hα/Hβ/Hγ ratios are steeper in the broad-line radio galaxies than in the Seyfert 1 galaxies. Another is that the Fe II emission features are much weaker

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in the broad-line radio galaxies than in the average Seyfert 1 galaxy, though there is a wide range in strength of these features in Seyfert 1 galaxies and a few are known with Fe II weak or unobservable. Very strong variations in the H I emission-line profiles have been observed in one Seyfert 1 galaxy, NGC 7603 (Tohline and Osterbrock 1976) and probably also occurred in two others, Mk 358 and Mk 291, since we have begun observing these objects.

Though the concept of the division of Seyfert galaxies into two classes, 1 and 2 as proposed by Khachikian and Weedman (1971) is a good one, it is not completely clearcut, and there are a few intermediate cases in which a strong narrow H I component with the same width and redshift as the forbidden lines is superimposed on a broad component characteristic of the Seyfert 1 galaxies. We might call such objects Seyfert 1.5 galaxies (Osterbrock and Koski 1976) but actually there seems to be a continuous variation in properties ranging from pure Seyfert 1 (broad H I profiles) to pure Seyfert 2 (narrow H I profiles with relative intensities $H\beta/\lambda 5007 \approx 0.1$).

Though nearly all the radio galaxies we observed may be classified either as broad (H I)-line radio galaxies, or narrow (H I)-line radio galaxies, one object falls outside both these groups. It is PKS 1345 + 12, which is being investigated by Grandi (1976). All the emission lines in this galaxy, recombination and forbidden, have intermediate widths (about 1200 to 1600 km s^{-1} full width at half maximum) and all have asymmetric profiles with similar forms. Furthermore, the [O III] and [Ne III] lines have a slightly different redshift from the other emission lines such as H I, [O I], [S II], [N II] and [O II]. Differences in redshift depending on level of ionization have previously been found in the Seyfert 1 galaxy I Zw 1 by Phillips (1976), but PKS 1345 + 12 is the only case known to me in which the profiles are similarly asymmetric, but the redshifts are different.

We have looked for correlations between the optical emission-line properties of radio galaxies and their radio properties. A relatively large fraction (about 2/3 in our sample) of the radio galaxies are narrow-line radio galaxies, the analogues of Seyfert 2 galaxies, although among Seyfert galaxies as a group, about 3/4 are Seyfert 1's, and only 1/4 Seyfert 2's (Khachikian and Weedman 1974). Likewise, of the ten Seyfert galaxies that have been measured as radio sources by de Bruyn and Willis (1974) or Kojoian et al. (1976), five are Seyfert 2's, and at least two of the remaining five, NGC 4151 and Mk 6, are better classified as Seyfert 1.5 than Seyfert 2 (Osterbrock and Koski 1976). In fact, four of the five broad-line radio galaxies (all except 3C 120) have this same type of composite broad + narrow H I lines profiles, strongly suggesting that the narrow emission-line spectrum is physically connected with the radio emission more closely than the broad emission-line spectrum is.

At the Minkowski Symposium, van der Laan (1976) pointed out that a larger fraction of radio galaxies with compact radio sources in their

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nuclei have emission lines in their spectra than of radio galaxies without compact sources. Among our sample a higher fraction of broad-line radio galaxies (3C 382 and 3C 390.3, two of five) are known to have compact central sources than of the narrow-line radio galaxies (Cyg A and 3C 452, two of eleven).

Practically all the radio galaxies have power-law spectra with indices $\alpha = 0.75 \pm 0.10$, while the Seyfert galaxies have a slightly larger range but essentially the same mean value. Only 3C 120 has a greatly deviant radio spectrum (Veron et al. 1974). In optical form, a large fraction of the broad-line radio galaxies are N galaxies, while more of the narrow-line radio galaxies are cD, DE or E galaxies (Mathews et al.1964). Many of the nearby Seyfert galaxies show signs of spiral structure, but their bright nuclei relate them closely to N galaxies (Morgan et al. 1971, Morgan 1971).

Besides 3C 390.3, several Seyfert-galaxy nuclei are known to vary in light in time scales as short as a month (see e.g. Selmes et al. 1975). All of them are Seyfert 1 galaxies. It appears that the optical activity is connected with the presence of high-velocity ionized gas, but that radio emission, though sometimes present in this phase, is more often observed in the "quiescent" phase in which the ionized gas has velocities of order 500 km s^{-1}. The similarity of both radio and narrow-line optical properties suggests that narrow-and broad-line galaxies are different stages in the evolution of one and the same type of objects. Since many of the broad-line galaxies are double radio sources, it seems likely that they have had earlier outbursts, and thus that they evolve back and forth between broad-and narrow-line stages.

Quasars, of course, appear very closely related to radio and Seyfert galaxies, and indeed much of the motivation for our optical study of the latter objects is our hope that they will help us to understand quasars. An excellent spectrophotometric survey of low-redshift quasars has recently been published by Baldwin (1975a). Most of them have optical spectra similar to broad-line radio galaxies and Seyfert 1 galaxies. The Fe II emission features are weak in the quasars, as in the broad-line radio galaxies, though two quasars, 3C 273 and PKS 0736 + 01 have Fe II strong (Baldwin 1975b), as in many Seyfert 1's. Otherwise the temperatures, densities, line widths and abundances seem quite similar in quasars and Seyfert 1 galaxies.

It appears that we are beginning to get optical measurements that are capable, at least in some cases, of distinguishing between different types of radio sources and Seyfert galaxies. The problems of refining these observations, and through them understanding the nature (or natures) of radio sources remain challenging problems for the future.

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references to radio measurements. I am also most grateful to the National Science Foundation for partial support of my research on these topics over the years.

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DISCUSSION

Rowan-Robinson: Does your V - 6 cm index refer to the visual magnitude of the nucleus or of the whole galaxy? Are the extinctions deduced in Type 2 Seyferts consistent with their absence of broad wings being due to dust?

Osterbrock: To the whole galaxy. No, I do not think that the same amount of extinction that is observed in the central narrow components of the HI lines in Seyfert 2 galaxies could possibly suppress broad wings of the type observed in Seyfert 1, or Seyfert 1.5 galaxies if they were also present in Seyfert 2's.

Wampler: You have shown that Seyfert Galaxies can be separated from Radio Galaxies by spectral and radio criteria. When this is done one finds that there is also a segregation in form as the radio galaxies are elliptical while the Seyferts are spiral. Would you like to comment on this?

Osterbrock: The separation appears to be very strong, though more work needs to be done on obtaining large-scale direct plates of Markarian and Zwicky Seyfert galaxies and classifying them. These differences must have physical significance, but I do not know yet what it is.

de Felice: Can you comment further on the observed separation between Seyfert Galaxies and Radio Galaxies regarding the FeII emission line strength?

Osterbrock: The fact that this correlation (weakness of FeII emission in broad-line radio galaxies) exists is extremely interesting but we do not understand the reason for it. Mark Phillips is working observationally on FeII emission in Seyfert galaxies, and we hope that his results will throw some light on how the excitation occurs, and therefore on the physical differences between broad-line radio galaxies and Seyfert galaxies.

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