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RADIO GALAXIES AND QUASI-STELLAR SOURCES

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The material contained here is intended to summarize the observational material on extragalactic discrete radio sources and to briefly describe some of the theoretical interpretation. No attention is paid to the various techniques used to obtain the data. The radio and optical properties of radio galaxies and quasi-stellar sources are discussed in Sections II and III; the theory of synchrotron radiation is reviewed and applied to the observations in Section IV. Section V discusses the implications of radio source statistics on Cosmology.

I. Introduction

In any study of radio galaxies (RG) and quasi-stellar sources (QSS) one might expect at least to learn the answers to the following questions: What is a RG? What is a QSS? What is the difference between a RG and a QSS? At the present time there are no simple answers to these questions. It is not clear what a radiogalaxy is, or why or how a galaxy becomes a radiogalaxy, or even just how to define a radiogalaxy as contrasted to a "normal galaxy". We certainly do not know what a QSS is and we are not even sure where they are. It is difficult to define precisely the difference between a RG and QSS, and we do not know what relation there is between a RG and QSS. Are they both the same phenomena on a different scale, or is the QSS an early stage of a RG, or perhaps a later stage? It is thought that both types of objects radiate by the synchrotron process caused by ultra relativistic electrons moving in weak magnetic fields. But the source of high energy particles and magnetic fields is a complete mystery. It may be the same for QSS as for RG or it may be different. We do not know.

What we do know is a wealth of observational data based on extensive radio and optical observations by many workers at many observatories throughout the world. There are many trends and patterns in the data which suggest that we are making some progress toward understanding these objects. But what is still lacking is a single unifying theory that brings together all the little bits and pieces. The situation may be compared with that of the atomic physicists and spectroscopists at the end of the 19th century who had numerous, if somewhat arbitrary, selection rules to explain the spectra of the elements, but awaited the development of quantum mechanics to really understand atomic phenomena. It may well be that we will have to make an equally drastic modification in the laws of physics before we fully "understand" the nature of RG and QSS.

No doubt this great confusion is due at least in part to the very rapid development of the subject. It has been less than 20 years that extra galactic origin of discrete radio sources was realized. It has been only about 10 years that large numbers of physicists and astronomers have become interested in the problem. And it has only been 6 years since the class of objects we now refer to as QSS's was realized to exist. For many years there was little interest among theoreticians, and most of the theoretical progress was made by workers in the Soviet Union. More recently the reverse has been true and numerous speculative papers have appeared constantly in the literature.

Ever since the discovery that the strong radio source Cygnus A was a relatively distant galaxy there has been much anticipation of the use of radio astronomy to solve the cosmological problem. This was further encouraged first when the source 3C 295 was found to have a red shift of ~ 0.45 and later with the finding of the very bright quasi-stellar sources and more numerous radio quiet quasi-stellar galaxies whose spectra were measured for redshifts greater than 2. It is safe to say that the breakthrough has not yet come. One of the greatest difficulties is the inability to determine distances from the radio measurements alone. So far it has been possible to obtain distances only from the measured red shift of an associated optical object. Moreover, there is general agreement that we need to know more about the objects (RG or QSS) involved before we can use them to do cosmology. An in fact it may very well be that the physics of RG and QSS will be more productive than the cosmology.

II. Optical Properties of Radio Galaxies and QSS

Discrete sources whose angular coordinates are precisely known can often be associated with an optically visible object by comparing the radio position with photographs of the sky. Typically, an accuracy of the order of $\pm 15''$ in each coordinate is required for a reliable identification. The positions of about 750 sources are known to this accuracy. Of these, about half are identified with either a galaxy or a quasi-stellar object. Of the unidentified sources, some have several objects within the error rectangle, and others have none.

Historically, galaxies have been divided into normal galaxies (NG) and radio galaxies (RG) according to whether they were first discovered by looking for a peculiar galaxy at the position of a strong radio source (RG) or by looking for weak radio emission from a bright galaxy (NG).

The normal galaxies are then weaker radio emitters than the radio galaxies, but this is at least in part a result of their definition.

Quasi-stellar radio sources (QSS) are radio sources which are identified with starlike objects alghough they are thought by most (but not all) to be extragalactic. According to Schmidt, a QSS has the following properties:

1) Their appearance is stellar.
2) They are on the average 4 magnitudes brighter than radio galaxies of equal red shift.
3) The optical light is variable.
4) The spectrum shows broad emission corresponding to velocities of about 4000 km/sec.
5) The optical distribution shows a large UV excess.

There is no clear cut difference in the radio properties of radio galaxies and QSS, although as discussed in Section III there are significant statistical differences. It is not possible therefore to differentiate between a radio galaxy and a QSS on the basis of radio measurements alone.

In addition, there are the so-called radio quiet quasi-stellar galaxies (QSG) which are not known to be radio sources but which are optically identical to the QSS. These are probably less luminous radio emitters than the QSS, but due to their great distance are not observable as radio sources. The radio quiet QSG's appear to be about 50 times more numerous than the radio active QSS's.

The term "quasi-stellar object" (QSO) is often used to refer to QSG's or to the optical counterpart of the QSS's. Probably intermediate to the radio galaxies and the QSS in optical structure are "compact" galaxies which are barely resolved with large telescopes and often appear nearly stellar.

Red shifts have been measured for approximately 150 QSS and about half as many radio galaxies. Only for these objects can distances, and thus absolute dimensions and luminosity, be estimated. The various types of objects in roughly the order of their radio luminosity are

Lum (ergs/sec)	10^{38}				10^{40}					10^{44}	10^{46}
	E	Sa	Sb	Sc	I	E	dB	D	N	QSG	QSS
	normal galaxies (E, Sa, Sb, Sc, I)					radio galaxies (I, E, dB, D, N)					

Normal ellipticals (E) are usually very weak radio sources and only a few have been detected. The luminosity increases as we go toward late type spirals which have radio luminosities comparable with our own galaxy. Only one spiral galaxy, 3C 305, is a strong source with $L \sim 10^{42}$ ergs/sec. The luminosity increases from the irregulars (I), the giant ellipticals which are usually the brightest member of a cluster, the dumbells (dB) which are double nuclei in a single envelope, D galaxies (D) which are single objects in an extensive envelope, the N galaxies (N) which have essentially stellar nuclei in a faint envelope, and the QSS. Some spiral galaxies with particularly active nuclei, known as Seyfert galaxies, are particularly prominent radio sources. Most of the radio galaxies are found to be in clusters with more than 50 percent in rich clusters. The QSS are not known to be in clusters, but there is no conclusive data that they are not.

Optical luminosity. Normal spirals generally have an absolute magnitude fainter than -21. The radio galaxies show a surprisingly small dispersion of absolute luminosity of $\pm 0.8^m$ about a mean value of -21. The QSS on the other hand have magnitudes between -23 and -26 and thus 10 to 100 times more luminous than the brightest galaxies.

Spectra. The spectra of radio galaxies often, but not always, show moderate to strong emission lines such as OII. Often an appreciable fraction of the luminosity is in the emission lines so that it is possible to obtain spectra of relatively weak objects. Red shifts of radio galaxies range up to 0.46 for 3C 295. The QSS always show strong broad emission lines of MgII, CIII, CIV, OII, OIV, $H\alpha - \epsilon$, NeIV, NeV, and other highly excited ions usually found in the spectra of planetary nebulae. The QSS red shifts are large but there is a sharp cutoff near $z \sim 2.3$. The continuum shows a strong UV excess which, due to the large red shift, often makes the object appear blue. They are also anonomously bright at infrared wavelengths.

Optical variations. Many QSO's, as well as the active nuclei of some galaxies, show optical variations on a time scale ranging from more than a year to less than one day. The general nature and form of the variations is, however, unclear. There is evidence in some sources of a periodic variation with periods ranging from a few months to many years. Many of the objects which show large optical fluctuations are characterized by a high degree of polarization. Both the amount and direction of the polarization has been observed to change significantly in a few weeks.

Optical polarization. Polarization has been detected in the radio galaxies M82 and 3C 120. However, in M82 the highly polarized filaments extend up to 10' away from the center of the galaxy. The connection between these filaments and the radio emission is unclear since the radio source is less than 0.5' in diameter and is located in the center of the galaxy. In 3C 120 the optical polarization appears to be coincident with the radio source. Among the QSS linear polarization has been detected from 3C 279 (15%), 3C 345 (8%), and 3C 446 (30%), and others. In 3C 446 the plane of polarization was found to rotate by 90° in only a few months time.

III. Radio Properties of Extra-Galactic Sources

As the sensitivity and angular resolution of radio telescopes have improved an ever increasing number of discrete sources have been found. In 1952, 100 sources were known. Today, about 6000 radio sources have been catalogued with reasonably well-established positions and flux densities at at least one frequency. These come mainly from three sky surveys:

1) The Cambridge 3C and 3CR	$\delta >$	6°	500 sources
2) The Parkes catalogues	$\delta <$	+27°	2000 sources
3) The Cambridge 4C catalogue	$\delta >$	-6°	5000 sources

In addition there are several newer surveys, now still in progress, which are able to locate more than 10^5 individual sources per sterudian.

The main properties of a radio source which characterize the radio emission are (a) its angular position in the sky which may serve to identify the source with an optical object, (b) the radio brightness distribution which related to the distribution of magnetic field strength and relativistic particle density, (c) the polarization which is a function of the magnetic field configuration, and (d) its flux density as a function of frequency and time, which may be used to determine the radio spectrum from which the electron energy distribution may be obtained.

1) Brightness Distributions. The three dimensional structure of extragalactic sources is usually inferred from observations of the angular brightness distribution projected on to the plane of the sky. Moreover, often only the brightness distribution in one dimension is determined.

Some details of the angular structure is known for about 1000 discrete sources, from interferometry and synthesis, lunar occultations, and measurements of interplanetary scintillations.

The great majority of extragalactic sources have angular dimensions less than a few minutes of arc. Half have total dimensions between 3" and 30". Some are as small as 0.001 second of arc. In general the angular size of the QSS are smaller than for the radio galaxies, although the former are found as large as 1' arc and the latter as small as 4" arc. The corresponding linear dimensions range from about one light year to more than one million light years.

When examined with high resolution, many sources show a surprising amount of structure, the most common configuration is the double structure where the majority of the emission comes from two components of nearly equal size and luminosity. Typically, the overall dimensions are about three times the size of the individual components and are symetrically located about the associated galaxy or QSO. Double sources with unequal components as well as triple or more complex sources are also observed. In all of these sources the majority of the emission occurs well outside the galaxy or QSO.

In other sources, the radio emission originates from a very small volume of space with dimensions comparable to the nucleus of a galaxy. Often one or more of these "compact" sources are coincident with more extended sources, and these are referred to as Core-Halo sources. Although over one-half of the radio galaxies have an extent greater than 15" arc, an average of 25% of the emission comes from regions less than 2" arc.

In the QSS's the condensation into small components is even more pronounced. The QSS's can be divided into two groups: (1) the very small radio diameter ones, which are often intrinsically very strong radio sources, often have a short wavelength flux excess, and are sometimes variable and (2) the larger diameter QSS's whose radio properties (luminosity, spectrum, size) comparable to the radio galaxies and are indistinguishable from the radio galaxies by radio measurements alone.

2) Polarization. Nearly all radio galaxies and QSS show some degree of integrated polarization ranging from 0.5 to 4% with the greatest value $\sim$ 20%. Typically, the integrated polarization is less at longer wavelengths, and there is some tendency for the more luminous high surface brightness objects to be less polarized. In general the plane of polarization rotates proportional to λ^2. Since the amplitude and sign of the rotation depends strongly on galactic coordinates it is thought that the rotation is due to Faraday rotation within our own galaxy. The degree of depolarization at longer wavelengths may also depend on galactic coordinates, but this is not clearly established.

The synchrotron theory predicts a degree of polarization 60% to 70% which is close to the amount observed in some regions of resolved sources where the polarized flux comes mainly from a region much smaller than the extent of the unpolarized emission. The depolarizing mechanism resulting in polarizations of only a few percent are unknown. It may be due to differential Faraday Rotation in the galaxy, in the source itself, or may be the result of twisted magnetic fields in the source.

3) <u>Radio Spectra.</u> Until a few years ago radio source spectra were thought to be relatively simple and contained little information other than to determine that the emission mechanism was of a non-thermal nature. The observations agreed at least qualitatively with the synchrotron theory in that sources appeared to have roughly power law spectra. That is, flux density (S) is proportional to $(\text{frequency})^{\alpha}$, so that a plot of log S vs. log f the spectrum is a straight line with slope, α. α is called the spectral index. Only for a few dozen sources were spectra known and only for $100 \lesssim f \lesssim 1000$ MHz. Generally, α was ~ -1. There was only one spectral line from neutral hydrogen at 21 cm, and there were no observed (or expected) time variations.

Today, the situation is more complex; the spectra of over 2000 sources are known, several hundred in reasonable detail. The observable frequency range now extends from 10 to 100,000 MHz, 10,000:1 in frequency range, compared to 10:1 in 1960. Most sources still have approximate power law spectra although there are many exceptions, particularly at short (cm) wavelengths. Time variations in the spectra of QSS and some galaxies have been observed over time scales as short as a few weeks. Although large number of spectral lines are now known, no lines other than the 21 cm line have been observed outside the Galaxy. The forms of spectral distribution can be classified according to their appearance on a log S - log f plot into the following categories.

<u>Class S.</u> These sources have a more or less straight spectrum (power law) over a wide range of frequencies. For 50% of the extra-galactic sources, the spectral index, α, lies in the range -0.75 to -0.95 with nearly all sources in the range $-0.25 \lesssim \alpha \lesssim -1.3$. All galactic non-thermal sources (supernova remnants) are in this class, although they have a much wider distribution of indices than the extra-galactic ones.

Class C sources have negative curvature, so that their spectral index becomes steeper at high frequencies. The curvature occurs over a relatively narrow range of frequencies, and both above and below the frequencies of curvature the index is constant. The typical difference between the high and low frequency indices is $\sim$ 0.5. The great majority of sources have C or S spectra.

Class C+ sources have positive curvature so that their spectra become more flat at short wavelengths. Most likely these sources are composed of two components with very different indices so that the steep component dominates at low frequencies and the flat component at high frequencies. Among the extended sources this type of spectrum is rare, indicating little variation of the spectral index within the source.

Class C_{max} sources have positive spectral indices at lower frequencies, reach a peak, and then have normal spectrum at shorter wavelengths. These sources all have very small angular dimensions consistent with the low frequency cutoff being due to synchrotron self-absorption in an optically thick sources (see Section IV). Most sources with C_{max} spectra are QSS, although by no means do all QSS have C_{max} spectra. The other sources are radio galaxies with particularly active nuclei (Seyfert galaxies) and have many other properties in common with the QSS (UV excess, strong emission lines).

Class C_{min} sources have normal power law spectra at low frequencies, reach a minimum and then increase toward shorter wavelengths. Usually the radio diameter is moderate at long wavelengths but very small where the spectral index is positive suggesting that C_{min} spectra are a composite of S and C_{max} sources. For example, the high frequency components of 3C 279, 84, and 120 have spectra similar to Class C_{max} and have low frequency extended components with power law spectra.

Class Cmplx. Some sources have even more complex spectra which show several maxima and minima.

It is found that in general the spectra of radio galaxies steepen at short wavelengths (Class C-) while for the QSS the spectral index either remains constant (Class S) or becomes very positive (Class C_{min}). The QSS with Class S spectra show a distribution of indices similar to that for radio galaxies. Moreover, their linear dimensions and radiated power are of the same order as found for radio galaxies; the other, flat or positive spectra QSS have very small angular dimensions and are systematically more luminous; they show a relatively narrow dispersion of absolute luminosity. Among the radio galaxies those with steeper spectra are the most luminous. The unidentified sources also have relatively steep spectra and these are also probably highly luminous galaxies beyond the limit of optical telescopes.

In 1965 Soviet radio astronomers made the dramatic announcement that the 920 MHz flux density of CTA 102 varied periodically by 30% in a period of 102 days and speculated on the possible origin of this unusual source as an extraterrestrial "super civilization". Examination of earlier records of this source as well as later observations by numerous observers at nearly = frequencies have failed to confirm the reported variations. Unfortunately, there is little data available during the period that the apparent variations were observed. The Soviets have not made available in the open literature the technical details of their antenna and receiving system. It is, therefore, difficult to evaluate the reliability of their data or account for the apparent discrepancy with other observers.

The first clear evidence for time variations in an extragalactic source was found by Dent from observations of 3C 273 over a 3-year period which showed a surprising 50% increase at 8000 MHz. Subsequent observations of 3C 273 and other sources by many observers have led to the detection of variations in more than 25 extragalactic sources. To the extent that any general picture exists, the variations appear to be random bursts of radiation characterized by a rapid rise in luminosity followed by a more gradual decay. The bursts typically appear first at short centimeter or millimeter wavelengths and then propagate toward longer wavelengths with reduced amplitude. The typical duration of a single burst at one wavelength ranges from a few months to a few years. The time required for a burst to propagate to decimeter wavelengths extends up to a few years. No significant variations have been reported at wavelengths longer than 40 cm, where the outbursts appear to be completely damped. All the variable sources are very small, with angular dimensions of the order of 0.001" arc or less. All have complex radio spectra which are thought to be the superposition of several bursts, each occurring at a different epoch.

IV. Theories of Extragalactic Radio Sources

1) Synchrotron Radiation. It is now generally accepted that synchrotron radiation from ultra relativistic electrons gyrating in weak magnetic fields is responsible for most, if not all, of the observed radio emission from discrete extragalactic sources. In this section we summarize briefly the basic results of the synchrotron theory as they apply to radio astronomy and in the following sections the theory is applied in an attempt to understand the origin and evolution of extragalactic radio sources.

A single electron spiraling in a magnetic field at ultra relativistic velocities [$(1 - \nu^2/c^2) << 1$] has its radiation concentrated in a cone of half angle $\Theta \sim E/mc^2$. An observer sees only a short burst of emission lasting only during the time Δt that the cone is pointed toward the observer $\Delta t \sim 1/\omega \sim \left(\frac{mc^2}{E}\right)^2$. The radiation is concentrated in the high order harmonics, $\eta = (E/mc^2)^2$, of the classical gyro frequency $\omega_g = eB/m$. The frequency distribution of the radiation is given by a complex expression conveniently represented by

$$P(\nu, E, \Theta) = 2.3 \times 10^{-22} B_\perp \nu/\nu_c \, F(\nu/\nu_c) \text{ ergs sec}^{-1} \text{ Hz}^{-1} \tag{4.1}$$

where

$$F(\nu/\nu_c) = \int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta) \, d\eta \tag{4.2}$$

and where $B_\perp = B \sin \Theta$ is the component of the magnetic field in cgs units perpendicular to the line of sight; $K_{5/3}(\eta)$ is a modified Bessel function; Θ is the angle between the electron trajectory and the magnetic field (pitch angle); and the critical frequency ν_c is given by

$$\nu_c = 1.6 \times 10^7 B_\perp E^2_{Gev} \text{ MHz} \qquad (4.3)$$

The spectrum of the observed radiation depends on the angle φ between the line of sight and the electron trajectory and on the plane of polarization.

The total power radiated by each electron is given by

$$dE/dt = A B_\perp^2 E^2_{Gev} \text{ ergs/sec.} \qquad (4.4)$$

where $A = 6.08 \times 10^{-9}$.

The distribution given by equation (4.1) has a broad peak near $\nu \sim 0.28 \nu_c$. For $\nu/\nu_c < 0.3$, $P(\nu) \propto \nu^{1/3}$, and for $\nu/\nu_c > 3$, $P(\nu) \propto (\nu/\nu_c)^{1/2} e^{-\nu/\nu_c}$ and the radiation rapidly falls off with increasing frequency.

For an assembly of electrons with a number density N(E)dE between E1 and E2, equation (4.1) can be integrated to find the total radiation at any frequency from all the electrons. Using (4.3) and making a change of variable this becomes

$$P(\nu_1 \Theta) = 4.1 \times 10^{-29} B_\perp^2 \nu^{1/2} \int_{\nu/\nu_1}^{\nu/\nu_2} \nu/\nu_c^{-3/2} N(\nu/\nu_c) F(\nu/\nu_c) d(\nu/\nu_c) \qquad (4.5)$$

where ν_1 and ν_2 are the critical frequencies corresponding to E1 and E2.

In the special case where the electron energy distribution is a power law, that is, $N(E)\,dE = KE^{-\gamma} dE$, equation (4.5) becomes

$$P(\nu_1 \Theta) \propto B^{(\gamma + 1)/2} \nu^{-(\gamma-1)/2} \int_{\nu/\nu_1}^{\nu/\nu_2} (\nu/\nu_c)^{-(3 - \gamma)/2} F(\nu/\nu_c) d(\nu/\nu_c) \qquad (4.6)$$

for $\gamma \gtrsim 1$ the major contribution to the integral is when $\nu/\nu_c \sim 1$ so that the limits of integration may be extended from zero to infinity with introducing significant error.

The integral is then essentially constant when $3\nu_1 \lesssim \nu \lesssim 10\,\nu_2$ so that the radia-spectrum is a power law

$$P(\nu) \propto \nu^{\alpha}$$

where the spectral index $\alpha = -(\gamma - 1)\ 2$.

It must be emphasized that this approximation is only valid when $\gamma \gtrsim 1$; and in particular that no form of energy distribution can give a spectrum that rises faster than the low frequency asymtotic limit of $\nu^{1/3}$ for a single electron.

Since many sources show nearly power law radio frequency spectra with a spectral index $\alpha \sim -0.8$ it may be concluded that the number density of relativistic electrons also has a power law distribution with respect to energy with an index $\gamma \sim 2.6$. Deviations from a constant radio spectral index may be explained as being due to (a) variations in γ as a function of energy; (b) self absorption in the relativistic electron gas; (c) absorption in a cold H II region between us and the source; (d) the effect of a dispersive medium in which the electrons are radiating.

a) Effect of Energy Losses. Even if relativistic electrons are initially produced with a power law distribution differential energy losses can alter the energy spectrum. Relativistic electrons lose energy by synchrotron radiation and by the Inverse Compton effect which are both proportional to E^2; by ordinary bremstrahlung and adiabatic expansion which are directly proportional to the energy, and by ionization which is proportional to $\ln E$. Approximating the logarithmic term by a constant the rate of energy loss may be written

$$\frac{dE}{dt} = aE^2 + bE + c \tag{4.8}$$

If electrons are being supplied to the source at a rate $Q(E, t)$, then the equation of continuity describing the time dependence of the energy distribution $N(E, t)$ is

$$\frac{\partial N(E, t)}{\partial t} = \frac{\partial}{\partial E}\left[\frac{dE}{dt} N(E, t)\right] + Q(E, t). \tag{4.9}$$

If at $t = 0$

$$N(E) = \begin{cases} K E^{\gamma} & E_1 < E < E_2 \\ 0 & E < E_1,\ E > E_2 \end{cases} , \tag{4.10}$$

and if synchrotron and Inverse Compton losses dominate and if there is no injection of new particles ($Q(E, t) = 0$), then

$$N(E, t) = \begin{cases} \dfrac{K E^{-\gamma}}{(1 - AB^2 Et)^{2 - \gamma}} & E_1' < E < E_2' \\ 0 & E < E_1',\ E > E_2' \end{cases}$$

where

$$E' = E/(1 + AB^2 Et)$$

Thus, even with an initial energy distribution extending to unlimited energy, there will be a cutoff at $Ec = 1/A\,B^2 \tau$ and a corresponding cutoff in the synchrotron radiation spectrum. In the special case where $\gamma < 2$, $N(E, t)$ can become very large for energies slightly less than Ec because of the piling up of the high energy electrons due to their more rapid rate of energy loss. If E_2 is sufficiently large so that $E_2'/E_c \sim 1$, then the radiation spectrum will become flat just below the upper cutoff frequency above which it sharply falls off.

If the distribution of electron pitch angles is random, then the cutoff frequency for each pitch angle differs and it may be shown that at low frequencies where energy losses are not important the spectral index, α remains equal to its initial value $\alpha_0 = (1 - \gamma)/2$. But at higher frequencies, $\alpha = (4/3\,\alpha_0 - 1)$. The frequency separating the two regions is given by

$$\nu_b \sim 1000\, B^{-3}\, t^{-2}_{\text{years}}\ \text{MHz} \tag{4.11}$$

If on the other hand relativistic electrons are continuously injected with $Q(E) = K\,E^{-\gamma}$, then for $\nu < \nu_b$ the spectral index remains constant with $\alpha = \alpha_0$. But at higher frequencies where the rate of energy loss is balanced by the injection of new particles $\alpha = (\alpha_0 - \frac{1}{2})$ This is obtained from the equilibrium solution of equation (4.9) with $\frac{\partial N}{\partial t} = 0$.

b) Effect of Absorption by Ionized Hydrogen. The observed radio spectrum may differ from the radiated spectrum due to the influence of the medium between the source and observer. If a cold cloud of ionized gas is located in front of the source then the observed flux density will fall off sharply below the frequency, ν_0 where the optical depth is unity. For an electron temperature T_e

$$\nu_0 \sim 3.6 \times 10^5\, T_e^{-3/2}\, \mathcal{E} \text{ MHz} \qquad (4.12)$$

where $\mathcal{E} = \int n_e\, d\ell$ is the emission measure, and n_e the density of thermal electrons. The observed spectrum is then

$$S \propto f^{\alpha}\, e^{-(\nu_0/\nu)^2} \qquad (4.13)$$

If the ionized medium is mixed with the synchrotron source then

$$S \propto \nu^{(\alpha + 2)} \qquad (4.14)$$

If the density of thermal electrons is sufficiently great then at frequencies where the index of refraction, η, becomes less than unity, the form of the spectrum will differ from that in vacua. When $\eta < 1$, the velocity of a relativistic electron is less than the phase velocity of light in the medium; the radiation is no longer so highly concentrated along the electron trajectory, and the energy no longer appears in the high order harmonics of the gyro frequency. It may be shown that this effect is important when

$$\nu \lesssim 20\, \frac{n_e}{B} \text{ MHz.}$$

c) Synchrotron Self Absorption. In all of the above we have assumed that the flux from a group of relativistic electrons is merely the arithmetical sum of the radiation of each electron, i.e., the electron gas is assumed to be optically thin. If, however, the apparent brightness temperature of the source approaches the equivalent kinetic temperature of the electrons, then self absorption will become important. The precise form of the radiation spectrum is complex, but can be calculated in a straightforward way from the emission and absorption coefficients of relativistic electrons in a magnetic field. These parameters depend on the electron energy and pitch angle distributions and can be determined only from numerical integrations. The form of the spectrum in the limiting case of an optically thick source may be derived quite straightforwardly, however. Consider the radiation from an optically thick black body.

$$S = \frac{2k}{c^2} \nu^2 T \Omega \qquad (4.15)$$

If the optically thick relativistic electron gas is thought of as a black body whose temperature is given by the equivalent kinetic temperature of the electrons, E = kT, then using (4.3) we can write

$$S \sim 10^{-3} \; B^{-1/2} \; \theta^2_{sec} \; \nu^{2.5} \; \text{f.u.} \qquad (4.16)$$

In other words, the source may be thought as a black body ($S \propto \nu^2$) whose temperature (energy) depends on the square root of the frequency ($E \propto \nu_c^{1/2}$). The frequency at which the optical depth reaches unity is

$$\nu_{\tau=1} \sim 16 \; B^{1/5} \; \Theta_{sec}^{-4/5} \; S_e^{-2/5} \; \text{MHz} \qquad (4.17)$$

where S_e is the extrapolated flux that would be observed in the absence of absorption.

From equation (4.17) it is seen that for a source of a few flux units and $\nu_{\tau=1} \sim$ 1000 MHz, $\Theta \sim 0.001''$ nearly independent of the magnetic field.

4) Energy Considerations. The entire question of the origin and evolution of extragalactic radio sources is one of the major unsolved problems of theoretical astrophysics; in particular the source of energy needed to account for the large power outputs is still a mystery. Assuming only that synchrotron radiation from ultrarelativistic electrons is responsible for the observed radiation, the necessary energy requirements may be estimated in a straightforward way.

If the distribution of relativistic particles is given by equation (4. 10), then the energy contained in relativistic electrons is

$$\mathcal{E}_e = \int_{E_1}^{E_2} E N(E)\, dE = \frac{K}{2 - \gamma}\left[E_2^{(2-\gamma)} - E_1^{(2-\gamma)}\right] . \qquad (4.18)$$

The constant K can be evaluated if the distance to the source is known; then the total luminosity of the source may be estimated by integrating the observed spectrum, then

$$L = \int_{E_1}^{E_2} N(E) \frac{dE}{dt}\, dE = \int_{E_1}^{E_2} AH^2 E^{(2-\gamma)}\, dE = A\frac{KH^2}{(3-\gamma)}\left[E_2^{(3-\gamma)} - E_1^{(3-\gamma)}\right], \qquad (4.19)$$

or

$$\mathcal{E}_e = \frac{3-\gamma}{2-\gamma}\;\frac{E_2^{(2-\gamma)} + E_1^{(2-\gamma)}}{E_2^{(3-\gamma)} - E_1^{(3-\gamma)}}\;\frac{L}{A} \qquad (4.20)$$

Using equation (4.3) to relate E_2 and E_1 to the cutoff frequency, and grouping all the constant terms together

$$\mathcal{E}_e = CLB^{-3/2} \qquad (4.21)$$

The magnetic energy is just

$$\mathcal{E}_m = \int \frac{B^2}{8\pi}\, dV = C' B^2 V \qquad (4.22)$$

The total energy in fields and particles ($\mathcal{E}_e + \mathcal{E}_m$) is minimized when

$$\frac{\partial \mathcal{E}}{\partial t} = 0$$

or when

$$B = \left(\frac{3}{4} \frac{C}{C'} \frac{L}{V}\right)^{2/7} \tag{4.23}$$

Then from equation (4.21), (4.22), and (4.23),

$$\mathcal{E}_e = 4/3 \ \mathcal{E}_m \tag{4.24}$$

That is, the energy is nearly equally distributed between relativistic particles and the magnetic field.

As an example, we consider the case of the Radio Galaxy Cygnus A. With $L \sim 10^{45}$ ergs sec and the volume taken to be two sources 40 kpc in linear extent, then $B \sim 10^{-4}$ Gauss, E_{total} 10^{60-61} ergs. This is the minimum energy required under the special conditions of equipartition. In general the energy may even be higher, particularly if there is a large number of relativistic protons, which do not contribute to the observed synchrotron radiation. Some estimates run as high as $M_p/M_q \sim 100$. It is largely because of this very great energy requirement ($\sim 0.01\%$ of the rest energy of an entire galaxy) that theoretical efforts to explain the origin of radio galaxies have been for the most part unsuccessful.

One consequence of having such a large store of energy is that the lifetimes of radio galaxies are very long, 10^8 to 10^9 years. Similar ages are obtained from the fraction ($\sim 10\%$) of giant elliptical galaxies that are found to be strong radio sources. One interesting result is that if $\mathcal{E}_e \sim \mathcal{E}_m$ the total energy strongly depends on the size of the source ($\mathcal{E} \propto r^{-9/7}$). This gives the curious situation that the larger sources with low surface brightness and low luminosity such as Centaurua A contain more energy than the smaller high surface brightness objects such as Cygnus A.

This is not, of course, what would be expected if as generally assumed the larger sources were older and has led to the interesting suggestion that sources may collapse rather than expand. One way out of this situation which also reduces the energy requirements on the larger sources is that if as recent observations suggest sources break up into a number of small components only a small fraction of the projected volume of a source actually has particles and a magnetic field. For this reason the energy requirements on the smaller QSS's are several orders of magnitude less than for the radio galaxies although their power outputs are usually greater.

The sources of energy proposed for extragalactic radio sources are as varied as the authors proposing them and are limited only by the imagination of the investigator. They range from the early theory of colliding galaxies which was not only highly improbable but which required a greater than 100% efficiency in converting energy into particles, to the more recent Soviet explanation of attempted intelligent communication from extra-terrestrial supercivilizations. Other ideas include numerous supernovae explosions, supernovae chains each setting off other supernovae, explosion of giant stars, collapse of giant stars, explosion of galactic nuclei, explosion of entire galaxies, galactic flares, collisions of stars, Matter-antimatter anhiliations, and Quark interactions.

For the most part the theories are vague at the best as to how all this energy is used to form relativistic particles or large scale magnetic fields. There are also many other important unanswered questions. Why do the particles always have a similar energy distribution in all sources, strong or weak, large or small, QSS or galaxy? Why are sources double or complex, some inside the parent galaxy - others far removed - sometimes much larger, sometimes much smaller than the galaxy? Why does the polarized emission often come only from a small region in the center? What determines if a galaxy or QSS becomes a radio source, what is the role of dust and jets, that are often found? What do the small compact QSO's have in common with giant ellipticals or with Seyfert galaxies? What is the role of the radio quiet QSG and how do the N galaxies fit into the picture?

At the present time it seems best to resist the interesting and provocative problem of the energy generation and to concentrate on trying to interpret the observations on the assumption that the necessary relativistic particles do exist in cosmic magnetic fields.. In this way, by inferring their energy distribution, spacial extent, and regeneration as well as properties of the magnetic field such as orientation and degree of order to impose sufficient restrictions on the problem of their original origin.

5) Models of Radio Sources. The simplest model which can account for the observed distribution of spectral indices and the detailed shape of individual spectra is one where the particles are generated in a series of recurring bursts with an energy index in the range $1 < \gamma < 2$. The initial spectral index α_0 is then ~ -0.25. At some later time the spectrum at low frequencies, where the decay time for the relativistic particles is longer than the period between bursts, the electron distribution is in equilibrium and $\alpha_0 = (\alpha_0 - 1/2) \sim -0.75$, a value near to that observed for the majority of sources. At higher frequencies electron energy losses steepen the spectrum to $\alpha = \left(\frac{4}{3}\alpha_0 - 1\right) \sim -1.3$, which is close to the high frequency index found in sources with dual power law spectra. Finally after the cessation of all activity the spectrum will further steepen to $\alpha = \frac{4}{3}(\alpha_0 - 1/2) - 1 \sim -2.0$ which is the extreme value found. The frequency separating the regions where the spectrum is $(\alpha_0 - 1/2)$ and $\left(\frac{4}{3}\alpha_0 - 1\right)$ is given by

$$f_0 \sim B^{-3}\,T^{-2}\ \text{GHz}$$

where B is the magnetic field in gauss and T is the period in years between successive outbursts.

In some currently active sources observations of the pronounced intensity variations provide direct evidence of repeated explosive events. In the simplest case a relativistic electron cloud is created in a single short burst and then expands at a constant rate.

If the magnetic flux is conserved in an expanding cloud which has a homogeneous and isotropic distribution of relativistic particles and a radius $\rho(t)$, then the following equation holds where the source is opaque

$$\frac{S_2}{S_1} = \left(\frac{t_2}{t_1}\right)^3$$

so that the flux density increases with time, and where it is transparent and has an energy index γ

$$\frac{S_2}{S_1} = \left(\frac{t_2}{t_1}\right)^{-2\gamma}$$

so the flux density decreases. The wavelength λ_m at which the intensity is a maximum is given by

$$\frac{\lambda_{m_2}}{\lambda_{m_1}} = \left(\frac{t_2}{t_1}\right)^{(4\gamma + 6)/(\gamma + 4)}$$

and the maximum flux density S_m, at that wavelength is given by

$$\frac{S_{m_2}}{S_{m_1}} = \left(\frac{\lambda_{m_2}}{\lambda_{m_1}}\right)^{-(7\gamma + 3)/(4\gamma + 6)}$$

The subscripts 1 and 2 refer to two epochs at which the observations are made.

In most variable sources the outbursts occur so rapidly that the emission from different outbursts overlap both in frequency and time and so a detailed quantitative analysis is difficult. To the extent that it is possible to separate events, individual outbursts seem to follow surprisingly well the simple model of a uniformly expanding cloud of relativistic particles and it has been possible to determine the date of several outbursts with an uncertainty of only a few weeks. The data indicate that the initial value of γ is in the range 1 to 1.5 so that the initial radio spectrum in the optically thin region is very flat. At least for one year following an outburst the expansion appears to continue at a constant rate and the value of γ is unchanged by radiation losses or by inverse Compton scattering. The superposition of many such events will eventually result in an extended source with a power law or dual power law spectra as described above.

In some sources the flux density, following a large outburst, remains at a high level for a year or more and sometimes shows small fluctuations indicating one or more minor outbursts. In other cases, however, the "flux curve" is very sharp, particularly at short wavelengths. This suggests that the duration of the bursts is not significantly broadened by the finite production time of the electrons, so that most of the production of particles probably occurs in less than a few months and the initial size must not be greater than several light months.

Among the resolved optically thick sources, the magnetic field is typically found to be about 10^{-4} gauss in the older, non-variable components, and 0.1 gauss or more in the younger variable components. Typically, the total energy involved in a single outburst ranges from about 10^{52} ergs in the nearby sources to 10^{58} ergs or more in the more luminous OSS.

V RADIO COSMOLOGY

One of the great goals of astronomy has always been to get a definitive picture of the large scale structure of the universe, its past and its future. We want answers to the questions, what is the nature of the universe at very large distances? How does it differ from the local region of space?

Until very recently there was almost no observational material bearing on this problem. Measurements show, that at least out to distances of about 10^9 light years the spectral lines in galaxies are shifted toward the red by an amount $z = \Delta\lambda/\lambda_0$ proportial to the distance, r. With r expressed in parsecs, the relation can be written $z = (H/c)\,r$. H is known as Hubble's constant. From observations of nearby galaxies H is thought to be about 100 km/sec/psc. If the spectral shift is interpreted as a doppler shift due to the expansion of the universe, then the velocity of recession of distant galaxies $v \sim zc$. The cosmological problem is to find out how the Hubble law behaves at very large distances, or because of the finite travel time for light, what the universe was like in the distant past. Many so-called cosmological models have been developed based on various solutions of Einstein's field equations. In some models the universe is continuously expanding at a uniform rate; in others it is accelerating, or deaccelerating, or even oscillating. In all of these models the density of the universe is constantly decreasing and there is a singularity at some time in the distant past where the radius was zero and the density infinite. To avoid this, the so-called "steady state" theory hypothesizes that universe has been and forever will be expanding, but that matter is continously created to keep a constant density . This is in contrast to the evolving universe, or "big-bang- theory where everything was created at once. In principal, observations at very large distances corresponding to $z \sim 1$, or $r \sim c/H \sim 10^{10}$

light years should be able to distinquish between the various models. Unfortunately even the largest optical telescopes can only measure red shifts of classical galaxies out to $z \sim 0.6$ and only a few galaxies are known with $z > 0.2$

Radio telescopes on the other hand may be able to detect radio sources from very much greater distances. In 1952 it was realized that the strongest radio source in the sky, Cygnus A, was a moderately distant galaxy with a red shift $z \sim 0.05$. By 1960 more than 50 radio sources had been identified with galaxies, the most distant being 3C295 which has a red shift $z \sim 0.46$ and is about the tenth strongest extragalactic radio source.

Once the extragalactic nature of most discrete radio sources was realized a very simple cosmological test was devised. Suppose that all sources have the same absolute luminosity and that they are uniformily distributed about the universe. Then the number of sources, N, in a volume defined by radius R is proportional to R^3. The observed flux density, S of each source is proportional to $1/R^2$. So the number of sources, N, observable above a given flux density is $N \propto S^{-3/2}$ or $\log N = -1.5 \log S + C$. If this is true for one luminosity, it is true for all luminosities. This is known as the log N - log S relation. It is of course equally valid at radio and optical wavelengths. However at optical wavelengths there are systematic errors in measuring the brightness of faint galaxies, which has precluded any definite conclusions being obtained from optical counts of galaxies.

The first serious radio tests were made in the mid 1950's. Counts based on the 1936 sources in the second Cambridge catalogue (2C) gave a slope of log N - log S $\sim$ -3. At the same time a survey of the southern hemisphere made in Australia gave a slope more nearly equal to -1.5

Clearly no cosmological model allows the universe to appear different from the northern and southern hemisphere. Moreover, a detailed comparison of the two catalogues in the region of overlap near the equator showed very little agreement. We now know that both the Cambridge and Australian surveys suffered from large experimental errors, due primarily to confusion by two or more sources in the antenna beam.

In the late 1950's, the third Cambridge survey (3C) gave a slope of about -2.2; and the fourth Cambridge survey (4C) completed only a few years ago gives -1.8. This latter value is confirmed, at least at higher flux levels, by other independent surveys.

This steep slope corresponds to an excess of weak sources over what would be expected in a universe where radio sources were uniformly distributed, this has been interpreted to mean that at great distances(or in the distant past) either the density of radio sources is greater, or their mean power is greater. Either of these is in violation of the "steady state" theory which requires the universe to be everywhere the same, and this result is usually taken as "proof" of the "big-bang" cosmologies.

The most recent surveys, however, show that at very low flux levels, the slope begins to flatten and is close to the expected -1.5. The proponents of the steady theory now argue that the steep slope found at high flux levels only represents a local deficency of strong sources, rather than a universal excess of weak sources.

The correct interpretation is still not clear. But an even more fundamental objection can be raised. Is it really possible to do cosmology by counting objects without knowing what you are counting? Clearly, one cannot do cosmology, if a significant fraction of the sources are say nearby stars in our own galaxy. Up until 1960, <u>all</u> the identified radio sources at high galactic latitudes . were identified with galaxies, and it was widely felt that <u>all</u> high latitude radio sources were in fact extra galactic. Continued efforts to identify more distant galaxies were concentrated toward small diameter high surface brightness sources on the reasonable assumption that these were probably quite distant. A primary candidate was 3C 48 which was the smallest strong source known with an angular size less than 1". Accurate position measurements produced what appeared to be unique identification with a 16th mag. stellar-object having a faint red wisp extending away from it. The absence of any other optical object near the radio source and the later discovery of significant night-to-night variations in light intensity lead to the reasonable conclusion that 3C 48 was a galactic star. Soon two other relatively strong sources, 3C 286 and 3C 196 were also identified with "stars" indicating that more than 20% of all sources were in this class thus creating considerable doubt on the use of radio source statistics to do cosmology. The optical and radio properties were suprisingly disimilar for the three objects and there were no unique radio properties to separate them from radio galaxies. 3C 48 and 3C 286 were unresolved radio sources (< 1") 3C 196 was about 12"; all three showed an UV excess and were above the black body line on a UBV diagram; 3C 48 had many strong emission lines none of which could be identified, 3C 286 had one, and 3C 196 none; the radio spectrum of 3C 196 was similar to normal radio galaxies, 3C 48 was slightly curved as in Cygnus A and 3C 286 very flat as for the galaxy M82.

Early efforts at interpreting the emission line spectrum of 3C 48 were relatively unsuccessful although the "possibility of a large red shift was considered". By 1962 most of lines were thought to be identified with highly excited states of rare elements. The identification of 3C 273 however, again created doubt on the galactic interpretation which by 1963 was widely accepted. 3C 273 was tentively identified in Australia with a 13th mag star from moderately accurate position determined with the 210' telescope. This was confirmed by a series of lunar occultation which showed that the radio source was double with one component having an unusually flat spectrum and being less than 1" away from the optical image. The other component with a more normal radio spectrum was elongated and coincident with a jet-like extension to the star. The identification was beyond question, although one wonders why it had not been made much earlier as 3C 273 was the brightest then unidentified source, of small angular size and located in an unconfused region of the sky near the galactic pole.

The optical spectrum of 3C 273 showed a series of bright emission lines which could only be identifed with the Hydrogen Balmer series $H_{\beta,\gamma,\delta,\epsilon}$ but with a red-shift of 0.16. This red shift was confirmed when the H_α line was found near the predicted wavelength of 7590 A°. This lead to the identification of the Mg II lines appearing at 3239 A° which had previously only been seen in the solar UV spectra taken from high altitude rockets.

A reinspectron of the 3C 48 spectrum led to a red shift of 0.37 if the strong feature at 3832 A° was identified with Mg II. Other lines could then be identified with OII, NeIII, and Ne V. Additional spectra taken of other similar sources led to the identification of C_{III} at 1909 A°, CIV at 1550 A° and finally $L_{y\alpha}$ permiting red shifts as great as 2.2 to be measured. As all quasi stellar objects were found to have a strong UV excess the search for further identification was simplified. Two photographs taken through different colour filters on the same plate served to locate very blue objects even without the aid of very accurate radio positions. Soon it was noticed that several such images often appeared well removed from the position of any radio source. These were call "Interlopers". As their numbers became more numerous they became refered to as Blue Stellar Objects (BSO) and it was recognized that their existence had long been known and many were in fact cataloqued in atlases of blue "stars". However, on the basis of number counts and colours Sandage concluded that the majority of BSO's fainter than 16th mag were in fact extragalactic and optically similar in nature to the QSS's although they appeared to be radio quiet. He called these objects Quasi Stellar Galaxies (QSG) and showed that three in fact had a large red shift. The ratio of QSG's to QSS's appeared to be about 1000 to 1. More recent observations ~~of~~ have shown that the ratio is more like 50 to 1 and at least some QSG's are weak radio sources.

The finding of large red shifts for relatively bright objects indicated absolute magnitudes as bright as -26 on the usual cosmological interpretation. This meant that QSG's were up to 100 times brighter than normal galaxies and could in principal be observed with optical telescopes ten times further than other galaxies, thus permitting a powerful attack on the cosmological problem.

However, at least for 3C 48 and 3C 273 evidence for light variations with time scales less than a few days led to the apparently unlikely situation of the existence of galaxies whose luminosity was equal to that of 100 ordinary galaxies and where most of the light came from a region less than one light year in diameter. The alternate explanation of a strong gravitational red shift in galactic objects led to equally implausible conditions.

Today, with a good deal more data including red shifts available on over 100 QSS's, there are three schools of thought on their locations: 1) that they are cosmological, 2) that they are local (in or near the Galaxy) and 3) that they are in between.

There are, however, serious objections to all these interpretations. The biggest difficulty is of course to explain the large red-shifts. In the cosmological model this implies large radio and optical luminosities which from the data on the time variations must come from very small regions of space.

Also there is the difficulty in explaining the absence of a mpg - red shift relation among the QSO's. That is if the red shift is related to distance one would expect the larger red shifts to be associated with apparently fainter QSO's. This is not observed to be the case. On the other hand it may be argued that if the intrinsic spread absolute in luminosity is large, then any magnitude-red shift relation will be hidden. The presence of large changes in apparent luminosity (up to 3 magnitudes in a month) gives support to this. Likewise for the associated radio sources there is no obvious flux-redshift relation, although if we restrict the comparison to small diameter optically thick sources such a relation may exist.

Another argument often used against the cosmological interpretation is that no QSO's are found in clusters of galaxies. The counter argument is that since QSO's are 5 magnitudes brighter than galaxies to be above the plate limit of ~21 mag. Also it has been stated that it would be difficult if not impossible to detect say a 20^{th} mag galaxy only 1' away from a bright 15^{th} mag QSO. At least for 3C 273 (13.5 mag) and 3C 48 (16.5 mag.) there are no galaxies down to the plate limit of 22 and 24.5 respectively. However, the faint jets associated with both objects would be of galactic dimensions if z were an indication of distance.

A more serious problem was thought to be due to the inverse Compton effect. When a radio photon collides with a relativistic electron the photon energy increase by an amount $(E/mc^2)^2$. For 1 Bev electrons radiating at 1000 MHz ($H = 10^{-4}$), $(E/mc^2) \sim 10^3$ and radio photons are raised to 10^{15} cps (optical). The ratio R, of I. C. losses to S. R. losses equals

$\frac{U_{rad}}{B^2/8\pi} \sim 10^5$ where U_{rad} is the energy density in the radiation field. It was thought that if R > 1, then the I. C. would become catastrophic since after a radio photon became an optical photon Urad was increased and R became even greater. That is optical photons would become X-Rays, X-Rays then γ rays, and the relativistic electrons would be immediately depleted. The only way around this is if B > 1 Gauss so that synchrotron loses were greater than I. C. losses. But then the electron lifetimes due to radiation loss are only a few minutes. Thus Urad must be decreased and this can only be done by bringing the source close - say < 50 Mpc. At first it appeared that these were conclusive arguments against the cosmological interpretation. But two factors were overlooked. First the I. C. cross section section decreases with increasing photon energy, so that optical photons interact only weakly with the electrons. Second if the radiation field and particle trajectories are not isotropic the I. C. effect is greatly reduced. For example if the electrons are streaming along a radial magnetic field with small pitch angles, then the electron and photon trajectories are in essentially the same direction and the I. C. radiation can be reduced by many orders of magnitude.

The main arguments against the local hypothesis are also the large red shift. The possibility of having large gravitational red shifts was considered from the beginning. Given a large massive body condensed to a small radius the gravitational red shift $z = GM/Rc^2$. For a body of 1 $M_\odot$, R $\sim$10 km. The observed width of the spectral line can be used to put a limit on the potential gradient in the region where the emission lines originate - $\frac{\Delta R}{R} = \frac{W}{\Delta\lambda} \sim .05$ so that the emission occurs in a thin shell of radius $\sim$10 km and thickness 1/2 km. The presence of certain forbidden lines puts a limit on the electron density $N_e < 10^8$ cm^{-3}. Knowing the density and volume of the radiating region and the observed H (β) flux the distance becomes less than that of the moon - an absurd value. Likewise increasing the mass up to 100 $M_\odot$ to 10^8 $M_\odot$ still puts the object at a distance where it will noticeably effect the motions of the solar system, local group of stars, or galactic system. Only with $M > 10^{11}$ $M_\odot$, and $R \sim 0.01$ psc giving $D \sim 25$ Mpc can a reasonable solution be reached. And for this case it is not at all clear whether the mass of a galaxy can exist in a space of a light year or less and be stable.

Another possibility is that the red shift is due to local doppler shifts, which are not part of the expansion of the universe. But in this case the lack of proper motions and of blue shifts makes this explanation unlikely. It has been suggested that QSO's were exploded from the center of the galaxy thus explaining the lack of blue shifts and proper motions. Then it is difficult to understand the source counts which show a slope of -1.8 for QSS, -1.5 for galaxies and -2.3 for unidentified sources. Since the unidentified sources are most probably galaxies beyond the 48" plate limit the combined galaxy + unidentified objects have slope -1.8, it seems that to a given flux limit galaxies and QSS cover the same volume of space.

One conclusive piece of evidence that 3C 273 at least is beyond all local hydrogen in the galaxy is the detection of 21 cm HI absorption from galactic hydrogen. A more controversal observation is the apparent detection from 3C 273 by HI. in the Virgo cluster located in the same line of sight. The inferred density of 10^{-29} gm/cm^{-3} is consistent with that found from the Virgo A absorption and would seem to indicate 1) that 3C 273 was at least beyond the Virgo cluster and 2) that there is significant HI in intergalactic space. This leads to the expection that for sources with $z > 2$ we should expect to see absorption short of the $L_{y\alpha}$ line now in the visable portion of the spectrum. This is not seen and the limit of intergalactic HI density is $< 10^{-35}$ gms cm^{-3} in apparent contrast to the 21 cm radio observation. It might be argued that all intergalactic matter is condensed into clouds but we should expect at least some QSO's to show a discontinuity at the $L_{y\alpha}$ wavelength. Also the condensation factor of 10^6 seems rather large. Moreover we should expect to see other absorption lines from clusters in front of QSO's with somewhat smaller red shifts. In fact in sources which show absorption line spectra about half have red shifts equal to the emission lines. Many others have an absorption red shift of 1.94 to 1.97. One object 0237-23 has several sets of absorption lines.

There is thus some evidence that the values of red shifts are not randomly distributed but have a preference for $z \sim 1.95$ or some multiple of 0.06 or 0.16. Likewise the emission line red shifts show an apparent deficit for $1 < z < 2$ and although there are about 10 objects with $z > 2$, none have values $z > 2.3$.

In fact if 1.95 represents an "intrinsic red shift", then the remaining cosmological red shift is $\sim .01$ or the distance less than 30 Mpc (H = 100 km/sec). Thus the observed red shifts would have little relation with actual distance.

This is in fact the conclusion of Arp who has studied the geometric coincidence between pairs of radio sources and peculiar galaxies. We have already noted a number of unusual coincidences which add weight to Arp's arguments such as the fact that 3 out of the 5 brightest sources at cm wavelength lie in a 15° circle; the similarity of several close radio pairs:

3C 343 and 343.1 which are 30' apart, but both less than 0".1 in size and both with pronounced spectral curvature; NRAO 512 and 3C 345 both small with flat spectra and variable which are 1° apart; 3C 273 and 1217 + 02 which are the QSO's with the smallest known red shifts and which both have flat spectra and which are 2° apart. Also there is the somewhat remarkable cm flux increase observed nearly simultaneously in 3C 273 and 3C 279 and the fact the two galaxies with the largest measured red shifts are only a few minutes of arc apart yet have quite different red shifts (0.46 and 0.36).

The acceptance of red shift as not being a distance indicator either for QSO's or galaxies is however difficult especially in view of its implication on astronomy. The clear distinction between local and cosmological theories can only be made from further analysis of existing and future radio and optical data. In this respect it should be noted that most of the effort so far has been in interpreting the wealth of optical data, and the radio measurements have served mostly just to spot the QSO's. As high resolution and high sensitivity radio telescopes come into operation and we learn more about detailed brightness distribution, spectra and polarization as a function of flux density we may then hope that the radio measurements themselves will give the missing clues to their interpretation. Perhaps then a definitive attack on cosmological problem will be possible.