QSOs AND RADIO GALAXIES – THEIR SPECTRA AND TIME VARIATIONS AT RADIO FREQUENCIES

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Abstract. Accurate relative spectra for 300 radio sources from the Parkes catalogue have been measured and a statistical study made of their relation to class of optical identification and to other radio properties. Individual spectra and their time variations have also been investigated.

The results support the contention that radio sources for which no identification appears on the Palomar Sky Survey prints may be galaxies more luminous at radio frequencies than those which are identified. From a study of QSOs, radio galaxies and these blank field objects, it appears (a) that with increasing radio luminosity compact components are more often found, their presence being indicated by synchrotron self-absorption at low and high frequencies, by flat, variable spectra at high frequencies, and by interplanetary scintillations; and (b) that where no compact component contributes to the spectrum at high frequencies, many spectra steepen with increasing frequency, an effect which may be more marked for the more radio luminous objects.

Detailed analyses of the time variations in the compact components of 22 variable sources are generally consistent with the adiabatically expanding, uniform sphere model of Shklovsky, Kellermann, van der Laan and others. The model was modified to include relativistic expansion according to the formulae given by Rees and Simon. The results suggest that these components have evolved within months or years, have linear dimension of 0.1 to 100 pc and magnetic fields of 1 to 10^{-4} G. Some spectra at frequencies above 5000 MHz suggest non-adiabatic expansion which may be the result of continued injection of energy into an expanding region.

1. Introduction

This paper presents the results of a study of the accurate spectra of 300 radio sources from the Parkes catalogue. The relations of these spectra to class of optical identification, radio luminosity, surface brightness, scintillation, polarization and time variability are investigated.

Observations of the accurate spectra were made between frequencies of 500 and 5000 MHz, using the 210-ft telescope and the 210–60 ft interferometer of the CSIRO Division of Radiophysics, at Parkes, Australia. These data have been combined with flux densities measured by other observers to obtain spectra for many of these sources over the frequency range 10 to 10000 MHz. Complete data on the new Parkes flux densities and spectra are presently being prepared for publication (Harris, 1970a). Detailed results of an investigation of these spectra, including their variability with time, are also in preparation (Harris, 1970b, c).

Examples of radio spectra are shown in Figure 1, which illustrates their qualitative classification. The spectra have been classified as having: (a) power law between 100 and 5000 MHz (Figure 1(a)); (b) negative curvature below 100 MHz (Figure 1(b)); (c) negative curvature above 1400 MHz (Figure 1(c)); (d) positive curvature above 1400 MHz (Figure 1(d)).

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Polynomial curves have been fitted to all data by the method of least squares. The main objection to this method is that spectra cannot always be represented by simple polynomials. An alternative method, of fitting two linear spectra above and below a 'break' frequency near 600 MHz has been used by Kellermann *et al.* (1969) and Shimmins (1968), to study the statistics of curvature. Few spectra show this break clearly; others are better fitted by a more gradual change in spectral index. This may be expected if physical conditions vary throughout the emitting region, as implied by

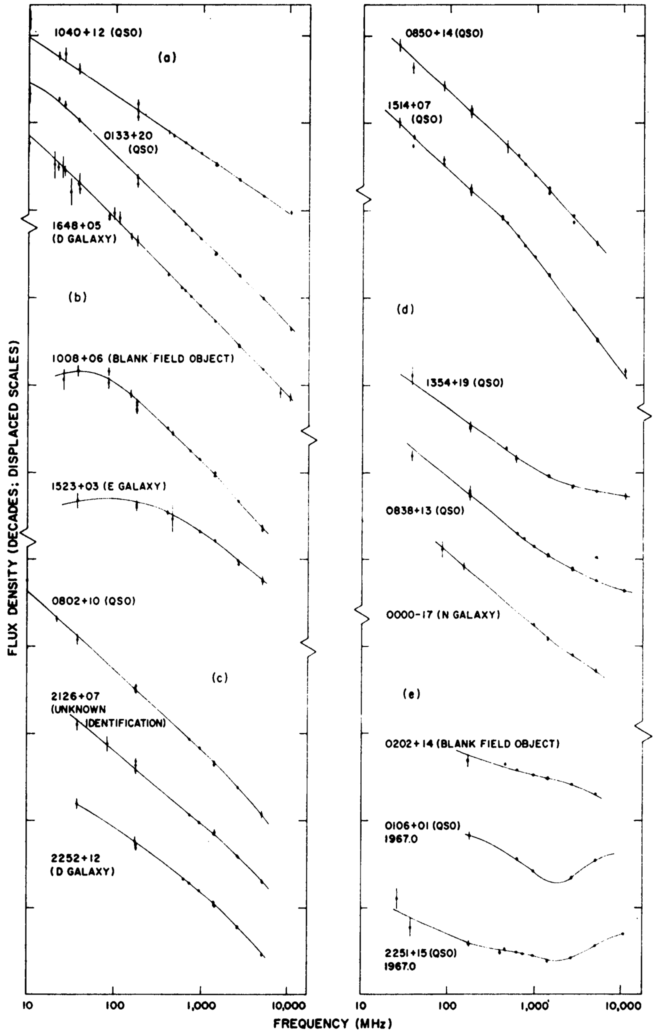

Fig. 1. Examples of spectra from the sample of 300. The following spectral classifications are illustrated: (a) power law spectra, between 100 and 5000 MHz; (b) spectra having negative curvature below 100 MHz; (c) spectra having negative curvature above 1400 MHz (two spectra having well defined 'break' frequencies are shown at upper right); (d) spectra having positive curvature above 1400 MHz; (e) complex spectra. The epoch is given for variable spectra. Note that PKS 1514 + 07 is identified with a D Galaxy, not a QSO.

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observed brightness distributions (for example, Ekers, 1969). Where spectra are more complex than power law, polynomial fitting is the only solution.

Spectral indices α, curvatures, and flux densities were calculated from the fitted curves at observed frequencies f of 400, 1000 and 4000 MHz. These frequencies span the observed frequency range of most spectra, avoiding the extreme ends of the range where the fitted polynomial tends to diverge from the data.

The optical fields of the 300 radio sources have been examined on the Palomar Sky Survey prints by Bolton and others at the CSIRO Division of Radiophysics. The optical fields have been classified as containing:

(a) a galaxy. These have been further classified as S (spiral), E (elliptical), D, db (dumbbell), N, or 'faint' (too faint to be classified);

(b) a quasi-stellar object (QSO). All QSOs have been confirmed, most by their optical spectra, a few by their ultra-violet excess;

(c) no likely optical candidate within two standard deviations of the radio position. Unidentified radio sources whose optical fields are crowded or obscured were rejected from the present sample.

2. The Spectra and Radio Variability of QSOs, Radio Galaxies and Blank Field Objects

A. THE RELATION BETWEEN SPECTRA AND IDENTIFICATION CLASS

The number distribution with respect to the classes of radio spectra for QSOs, S, E, D, db, N, faint galaxies and blank field objects is summarised in Table I, and is discussed below:

(a) Spectra of power law form between 100 and 5000 MHz. There is a significantly smaller percentage of power law spectra in the QSO class than in the galaxy class. There are no power law spectra amongst blank field objects. Although data from studies of sources found in low frequency surveys were used to interpret spectral shape near 100 MHz, these conclusions are also expected to apply to the present sample selected at the higher frequencies of the Parkes 408–1410 MHz survey.

(b) Spectra having negative curvature below 100 MHz. If this negative curvature is attributed to synchrotron self-absorption by regions of different optical depth throughout the radio source angular dimensions of $0\farcs1$ to $1''$ are implied. The figures therefore show that roughly equal percentages of QSOs and galaxies emit an appreciable fraction of their radiation from regions of these dimensions, and that more than half of the blank field objects contain structure of this order. For many sources these small angular sizes are confirmed by observations of interplanetary scintillation and very long baseline interferometry. Since the low frequency curvature is determined mainly from flux densities of sources found in low frequency surveys, this result is applicable only to sources common to both the low and higher frequency surveys.

(c) Spectra having negative curvature above 1400 MHz. The fraction of sources having steeper spectra at high frequencies increases strikingly from QSOs, through galaxies to blank field objects. As will be shown later this trend is also followed in the degree of negative curvature. Some spectra having different spectral indices above and

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TABLE I

Relation between optical identification and spectrum class

Class		QSOs	Galaxy types						All galaxies	Blank field objects
			S	E	D	db	N	faint		
(a) Spectra having power law between 100 and 5000 MHz	Number	9	0	12	12	4	1	4	33	0
	Percent of sample	22	0	28	52	50	14	36	35	0
	Total no. in sample	41	5	42	22	8	7	11	95	28
(b) Spectra having negative curvature, below 100 MHz	Number	16	4	12	5	4	3	5	33	17
	Percent of sample	38	50	27	20	60	40	55	33	50
	Total no. in sample	42	8	44	25	7	7	9	100	32
(c) Spectra having negative curvature, above 1400 MHz	Number	8	2	22	9	1	2	6	42	22
	Percent of sample	15	25	45	33	11	22	55	37	71
	Total no. in sample	53	8	49	27	9	9	11	113	31
(d) Spectra having positive curvature, above 1400 MHz	Number	16	0	2	1	0	3	0	6	1
	Percent of sample	30	0	4	4	4	33	0	5	3
	Total no. in sample	53	8	49	27	9	9	11	113	31

below a 'break' frequency fall in this class; examples are illustrated in Figure 1(c).

(d) Spectra having positive curvature above 1400 MHz. Whereas the low frequency spectra of QSOs and galaxies are indistinguishable, the same is not true above 1400 MHz. For 30% of the QSOs the flux density increases with increasing frequency. This is attributed to components of the source which become optically thick above 1400 MHz. Apart from Seyfert galaxies, which are excluded from these statistics, and N galaxies, this property is rare in the other radio sources. This result for QSOs has been given previously for a similar sample (Shimmins, 1968).

B. THE SPECTRA OF BLANK FIELD OBJECTS

One of the most important results of the present study is the continuous and marked negative curvature characterizing the spectra of nearly all blank field objects. This may be due in part to the redshifting of the high frequency spectra of distant galaxies into the observed frequency range. However, the high frequency observations of galaxy spectra (for example at 8000 MHz by Dent and Haddock, 1966) do not seem to support this explanation.

In general, above 600 MHz, this continuous curvature is more likely a result of aging than synchrotron self-absorption. Below about 600 MHz, synchrotron self-absorption is a probable mechanism.

C. COMPLEX SPECTRA

Examples of these are shown in Figure 1(e). Other examples include PKS 1434+03, 0859−14, 1229−02 and 1603+00. All complex spectra may be attributed to composite spectra of several emitting regions at least one of which is optically thick in the observed frequency range. Most are variable.

D. TIME VARIATION AND OPTICAL IDENTIFICATION

The previously detected time variations occur predominantly in QSOs. Only two galaxies, both of the Seyfert type, were observed to vary. Most of the radio sources were observed at least twice at 2650 and/or 5000 MHz. As the most accurate flux densities are available at these frequencies, and also as past observation and theory show that time variations are more probable at the higher frequencies, the following statistics will employ these data.

Table II gives for each identification class, the number of sources observed at least

TABLE II

Variability as related to flat and steep spectra for QSOs, radio galaxies and blank field objects

Identification class	Type of spectrum[a]	Number having 2 well-spaced observations at 2650 and/or 5000 MHz	Number found to vary	
			definitely	possibly
QSOs	steep	27	0	0
	flat	35	16	7
Galaxies	steep	62	0	1
	flat	7	4	1
Blank fields	steep	13	0	1
	flat	7	0	1
Others[b]	steep	12	0	1
	flat	9	4	1

[a] The division between steep and flat spectra is made at $\alpha_{1000} = 0.5$.
[b] Most of the identifications classed as 'others' could probably be included with the blank field objects; many are sources whose original identifications were rejected because they show no UV excess, or for which a more accurate position became available during the course of observations.

twice at 2650 and/or 5000 MHz, where the interval between observations was longer than 2½ months. This number is compared with the number of sources in which time variations were detected, either definitely or possibly. The statistics for sources with steep spectra, and those having flat or positively curved spectra at high frequencies, are compared.

These results show that variability was detected in about 60% of the 'flat' spectrum sources, regardless of identification. This figure is certainly a lower limit to the true number of variable sources as the observations were not ideally spaced in time; also as many of the variations are known to be small, others must fall within the errors of measurement. For all identifications and blank field objects less than 2% of steep spectrum sources were found to vary. These findings are in essential agreement with those of Medd *et al.* (1968) at 10630 MHz, although they found definite variations in PKS 0518+16 (3C 138) and 3C 196, both of which have steep spectra at lower frequencies.

E. COMPARISON OF SPECTRAL INDEX AND CURVATURE BETWEEN QSOS, GALAXIES AND BLANK FIELD OBJECTS

Table III shows mean spectral indices α with their dispersions σ_α.

TABLE III
Mean spectral indices for QSOs, radio galaxies and blank field objects

Class of identification	Approx. no. of objects	$f = 200$ MHz		$f = 1000$ MHz		$f = 4000$ MHz	
		α	σ_α	α	σ_α	α	σ_α
QSOs	59	0.62 ± 0.05	0.37	0.67 ± 0.04	0.29	0.67 ± 0.05	0.34
All galaxies	120	0.65 ± 0.04	0.42	0.72 ± 0.02	0.23	0.85 ± 0.03	0.32
Blank fields	31	0.58 ± 0.05	0.28	0.73 ± 0.04	0.24	0.92 ± 0.04	0.25

Apart from the faint, unclassified galaxies, no significant distinction was found among various kinds of galaxy. Note that the results are not corrected for selection, which will reduce the numbers of steeper spectra at low flux densities particularly if the dispersion in spectral indices is large, as for QSOs. Because the ranges of flux density covered by different classes of object are similar, comparison of their mean spectral indices is still valid, but the above selection effect would tend to mask distinction between these classes.

While the mean spectral indices at low frequencies are very similar for the three classes there is a progressive increase in high frequency index from QSOs to galaxies to blank field sources. The flux densities relative to QSOs differ by 18% for galaxies to 30% for blank field objects at 4000 MHz. Figure 2 illustrates the above result in the form of histograms of spectral indices. Gaussian distributions were assumed in evaluating the dispersions of the spectral indices. This is a close approximation for galaxies and blank field objects. For QSOs the distribution has a tail of flat spectra which accounts for their lower mean spectral index and higher dispersion. At 1000 MHz the peak spectral index is 0.82 ± 0.06, values similar to those found for galaxies and blank field objects.

Kellermann's theory of the evolution of radio spectra for recurring injection of relativistic electrons predicts distinct spectral regions. The region $f_{\text{MHz}} > 10^3 B_G^{-3}\, t_{yr}^{-2}$ where synchrotron losses predominate, is steeper by ~ 0.5 than the region $f_{\text{MHz}} < < 10^3 B^{-3} t^{-2}$, where these losses are balanced by recurring influx of particles. The maximum possible spectral index difference due to this effect is about 0.5 and occurs over a 10 to 1 frequency range. This is consistent with the data except where synchrotron self-absorption is affecting the lower frequencies; usually the difference is significantly less than 0.5 which would imply a variation in 'break' frequency through-

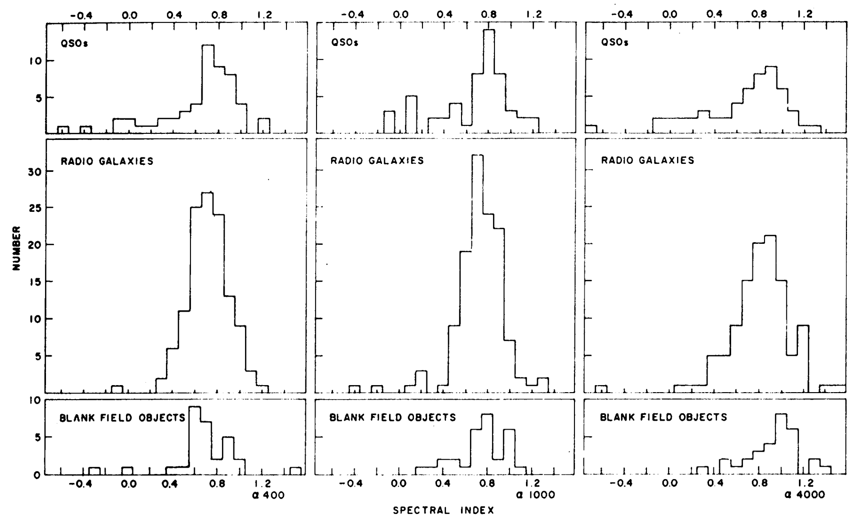

Fig. 2. Histograms of spectral indices α_{400}, α_{1000} and α_{4000} at frequencies of 400, 1000 and 4000 MHz, for QSOs, radio galaxies and blank field objects.

out the emitting region. The linear nature of the spectra of many sources over a wide frequency range implies that their equilibrium electron energy distribution is similar throughout this region.

3. Correlation of Spectra with Other Radio Properties

A. CORRELATION OF SPECTRAL INDEX AND LUMINOSITY

Figure 3(a, upper) shows the spectral index, α_{1000}, for E galaxies plotted against V_c, the photoelectric visual magnitude with correction for galactic absorption and *K*-effect. Figure 3(a, lower) shows α_{1000} for all identifications plotted against redshift for galaxies. At least for E galaxies, there is a suggestion of steepening of spectra with increasing luminosity (or redshift). It is not clear whether the lower boundary of spectral indices for QSOs may continue this trend to higher luminosities (or redshifts). Observational selection cannot account for the steeepening of galaxy spectra with redshift, since the distribution of redshift is essentially independent of flux density.

To investigate further whether spectra steepen with luminosity rather than with redshift, spectral index has been graphed against the logarithm of luminosity at 400 MHz, $\log P_{400}$, for galaxies at approximately the same distance in Figure 3(b). To increase the numbers of sources and extend the luminosity range, data have been taken from Kellermann (1964) for the strong, extended galaxies Fornax A, Centaurus A, and Virgo A, and also from Hobbs *et al.* (1968) for Cygnus A. The separate graphs for different ranges of V_c suggest the interpretation of a luminosity dependence of spectral index.

Kellermann (1966) has suggested that the more luminous radio sources have greater

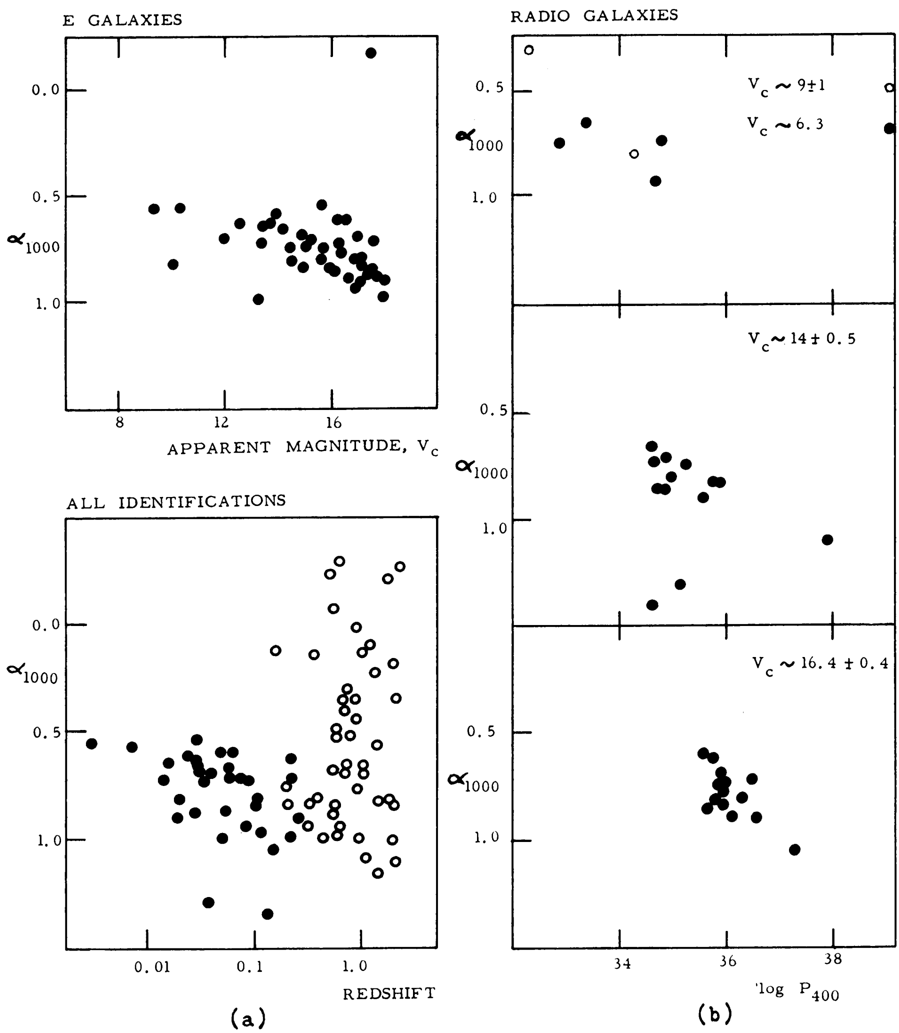

Fig. 3. (a, upper) The spectral index α_{1000} at 1000 MHz for E galaxies plotted against V_c, the photoelectric visual magnitude with correction for galactic absorption and *K*-effect; and (a, lower) for all identifications vs redshift, (b) spectral index α_{1000} vs $\log P_{400}$ where P_{400} is the luminosity at 400 MHz, for different ranges of V_c as indicated.

emissivities and hence evolve more rapidly. The steeper spectral indices could then be a consequence of this.

B. THE LUMINOSITY – SURFACE BRIGHTNESS DIAGRAM

The logarithm of luminosity at 400 MHz has been graphed against the logarithm of surface brightness (not shown). Surface brightness, or a lower limit, has been calculated using available data on brightness distributions found from long baseline interferometry and interplanetary scintillations. The same general trends are apparent as in the diagram by Heeschen (1966) or Longair and Macdonald (1969). These trends are:

(a) for radio galaxies, increase in luminosity roughly proportional to surface brightness which is well defined toward the upper left of the diagram, but poorly defined to right (high surface brightness);

(b) for QSOs, a horizontal branch of high luminosity which joins the galaxy branch at low values of surface brightness and extends to $B_{400} > 10^{-13}$ W m^{-2} ster^{-1} Hz^{-1}.

Heeschen interprets the diagram in terms of an evolutionary sequence in which an optically thin cloud of relativistic electrons expands, thus decreasing the surface brightness while maintaining constant luminosity. On approaching the branch at low surface brightness the expansion is retarded by magnetic fields and/or the intergalactic medium, so that further evolution occurs with constant or slowly increasing source dimensions. Luminosity decreases as particle energies decay, and the surface brightness decreases proportionally.

The relative positions of QSOs and galaxies in the luminosity-surface brightness diagram indicate a similar evolutionary pattern for both, but with reduced luminosity in the case of radio galaxies.

C. SPECTRAL INDEX AND LINEAR DIMENSIONS

If the above evolutionary scheme is correct, one might expect a steepening of the spectrum with decreasing surface brightness or with increasing linear dimensions as particle energies decay. The steep spectra of the extended halos about some individual radio galaxies are well known (for example, Ekers, 1969; Macdonald *et al.*, 1968). For galaxies a trend of increasing spectral index with surface brightness was found. This may be accounted for by the spectral index – luminosity and luminosity – surface brightness relations. Apart from this the present results show no correlations between spectral index or curvature with surface brightness or overall source dimensions, above a 5% level of significance.

D. SPECTRAL INDEX AND INTERPLANETARY SCINTILLATIONS

The relation between spectral index and linear dimensions may also be studied through interplanetary scintillation. The detection of scintillation indicates that more than 50% of the flux density is radiated from a region of angular dimensions $<0''.2$ (for example, Gardner and Whiteoak, 1969). Since the observed range of linear size among radio sources is much greater than their range of distances, the presence or absence of scintillation implies the presence or absence of components of compact linear dimensions.

Mean spectral indices for scintillators and non-scintillators are given in Table IV for 400, 1000 and 4000 MHz. QSOs, galaxies and blank field objects are distinguished. Both steep and flat spectrum objects belong to the class of scintillating QSOs, whereas nearly all non-scintillating QSOs have steep galaxy-like spectra. The flat spectra may thus be associated with angular dimensions $<0''.2$. Because the observed range of flux densities is small compared with the range of linear (or angular) dimensions,

TABLE IV

Scintillation statistics for QSOs, radio galaxies and blank field objects

Identification class	Percentage of scintillators		α_{400}	α_{1000}	α_{4000}
QSOs	70	Scintillators (39)	–	0.55 ± 0.03	0.51 ± 0.03
		Non-scintillators (16)	–	0.78 ± 0.07	0.78 ± 0.07
Radio Galaxies	25	Scintillators (19)	–	0.78 ± 0.03	0.89 ± 0.03
		Non-scintillators (57)	–	0.74 ± 0.02	0.85 ± 0.02
Blank field objects	60	Scintillators (11)	0.43 ± 0.11	0.68 ± 0.07	0.94 ± 0.05
		Non-scintillators (7)	0.57 ± 0.05	0.75 ± 0.05	0.92 ± 0.05

compact components are always associated with high surface brightness for QSOs. For a flux density of 10×10^{-26} W m^{-2} Hz^{-1} at 300 MHz, and angular diameter $<0''.1$, $T_b > 10^{10}$ K, so the flat spectra are probably a result of synchrotron self-absorption.

For the galaxies, 14% of those brighter than $17^m.0$ scintillate compared with 48% of the fainter galaxies. This can be explained by the decreasing angular size with increasing distance. As shown in Table IV the scintillating galaxies have a larger mean spectral index than the non-scintillating galaxies. This difference is of marginal significance; it is the result of the spectral index – luminosity and luminosity – distance relations.

The results for blank field objects imply: (a) that if they are of similar radio structure to the galaxies, they contain a higher proportion of scintillators by virtue of their greater distances; and (b) that those with the flattest spectra at frequencies near 400 MHz (and hence of highest surface brightness) contain structure on the smallest scale. These flat spectra are accounted for entirely by self-absorption and not by a flat, presumably young, electron energy distribution. At 4000 MHz there is no significant difference in spectral index between the scintillators and non-scintillators.

E. SPECTRA AND POLARIZATION

For QSOs, α_{1000} has been plotted against percentage polarization at 2650 MHz (not shown). There are significantly more flat spectrum objects having low polarization than high polarization (at the 5% level of significance on a chi-squared test). This trend is not evident for 1410 MHz polarization. This result is consistent with the lower average polarization found for sources having compact components at high frequencies. The explanation may be that magnetic fields are highly disordered in young objects. Fields become aligned as the source expands, resulting in a higher degree of integrated polarization, as in the halo components of radio galaxies (for example, Morris and Whiteoak, 1968; Seielstad and Weiler, 1969). This would be in general agreement with the model proposed by Gardner and Whiteoak (1969). The large scatter in percentage polarization for steep spectrum objects may be due in part to different orientations of the magnetic field to the line of sight.

No other correlations were found (at the 5% level of significance) between spectral index or curvature, and percentage polarization at 1410 or 2650 MHz, or depolarization (as measured by the ratio of degrees of polarization at these frequencies). Nor were any significant correlations found between percentage polarization at 2650 and 1410 MHz and luminosity, redshift, or surface brightness although there is some indication that for radio galaxies a high percentage of polarization is associated with low surface brightness, and low luminosity.

4. Time Variations of Spectra

Observations of time variations of spectra in the northern hemisphere to December 1967, have been reviewed by Kellermann and Pauliny-Toth (1968). They have applied the theory of an adiabatically expanding cloud of relativistic electrons to determine ages of the order of a few years for six sources whose flux densities have been well observed as a function of time and frequency. These authors have clearly demonstrated the good fit of the expanding source model to time variations observed in the Seyfert galaxy 3C 120 (PKS 0430+05) for frequencies below 5000 MHz. Locke *et al.* (1969) and Medd *et al.* (1968) report that observations at 6600 and 10600 MHz are generally consistent with the theory, although the simple model does not appear to explain the variations of PKS 1510−08, PKS 0763+01 and NRAO 512.

Variable spectra of 22 sources amongst the present sample have been analyzed individually in the light of the expanding source model of Kellermann, van der Laan, Shklovsky and others. However, this model was modified to include relativistic expansion according to the theory of Rees and Simon (1968).

In many cases linear extrapolation of the low frequency spectrum was assumed in order to extract higher frequency, optically thick components. Examples of the time variations of flux density and spectra for three sources are given below.

A. PKS 0430+05 (3C 120, SEYFERT GALAXY)

Comparison of the variations of flux density (Figure 4(a)) illustrates strikingly the time delay between the same event at different frequencies. Figure 4(b) gives the total observed spectrum in 1968.2. Figure 4(c) gives the spectra of the time varying components for several epochs, obtained by subtracting the spectrum of constant component A, assumed to be an extrapolation of the low frequency spectrum. Figure 4(d) shows the variable spectrum at three epochs analyzed into components C, D, E and F. Component B is not well determined and may not even exist. Component F may not be distinct, but may be an indication of continued outbursts at higher frequencies. These components may be determined uniquely, if their spectral indices in the optically thick region are assumed to be -2.5. For components C, D, and E the expansion ages at epoch 1968.2 are 3.0, 3.3, and 0.8 yr, respectively. If E is identified with the component having angular size $<0\overset{''}{.}0008$ found from very long baseline interferometry by Kellermann *et al.* (1968) and Clark *et al.* (1968) then $B<2.4\times10^{-3}$ G in 1968.1.

The angular diameters of the components of PKS 0336−01, 1127−14, 1226+02 (3C 273), 1253−05 (3C 279) and 2251+15 (3C 454.3) found from time variation theory have been compared with the diameters and limits to the angular diameters

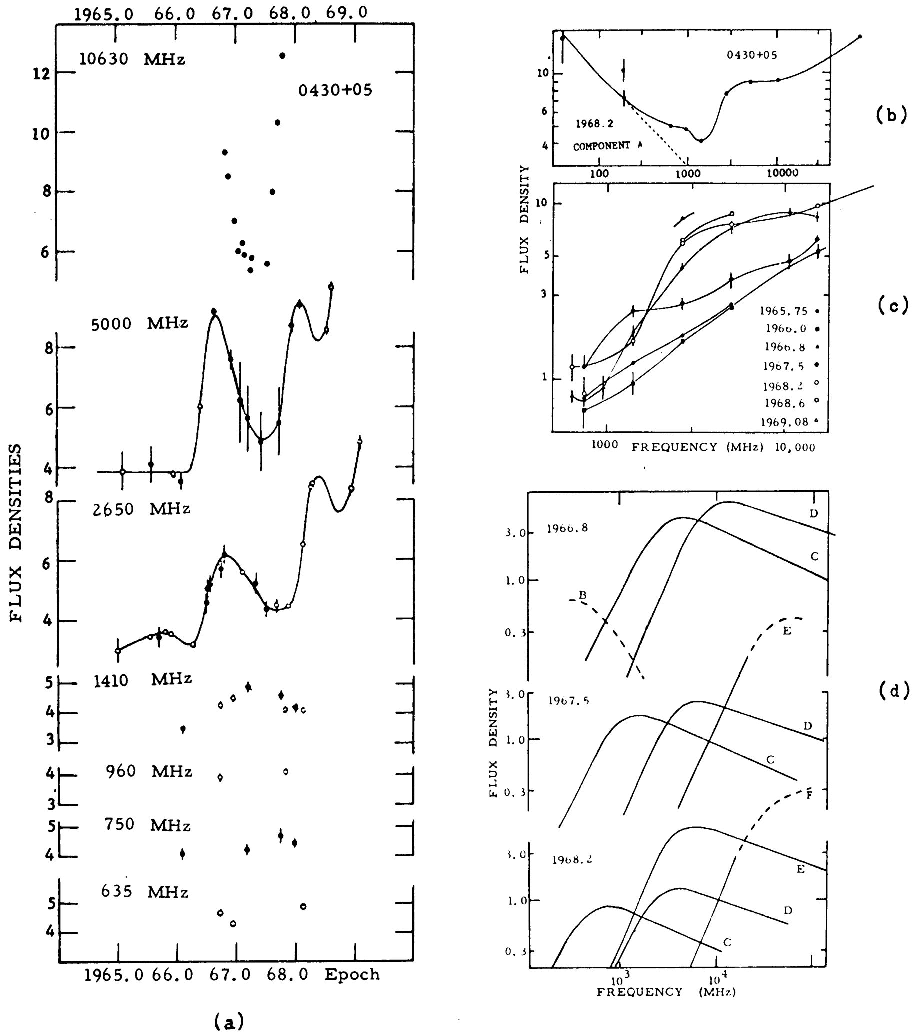

Fig. 4. The variable spectrum of the Seyfert galaxy, PKS 0430 + 05, showing (a) variations of flux density with epoch, at different frequencies; (b) the total observed spectrum in 1968.2; (c) the spectra of time-varying components at several epochs, found by subtracting the spectrum of component *A* from the total spectrum (spectrum component *A* at high frequencies assumed to be an extrapolation of the total spectrum at low frequencies); (d) analysis of the total variable spectrum, at three epochs, into components *C*, *D*, *E* and *F*. These components may be determined uniquely, if their spectral indices in the optically thick region are assumed to be −2.5. The open circles are data points from the present study. Closed circles are from other published results.

found from VLB interferometry. They show good agreement if magnetic fields are between 1 and 10^{-4} G within these variable components. The same is true for the sources 3C 84 and 3C 345.

The observations for most sources were consistent with the adiabatic, relativistic expansion model. The following are examples which do not appear to be consistent with adiabatic expansion:

B. PKS 0736+01 (QSO)

The Parkes observations at 2700 MHz bear out the very sharp decline observed at 6630 and 10630 MHz by Locke *et al.* (1969) (Figure 5(a)). The spectrum in 1967.74 (Figure 5(b)) shows no detectable high frequency components. In 1968.62 flux densities

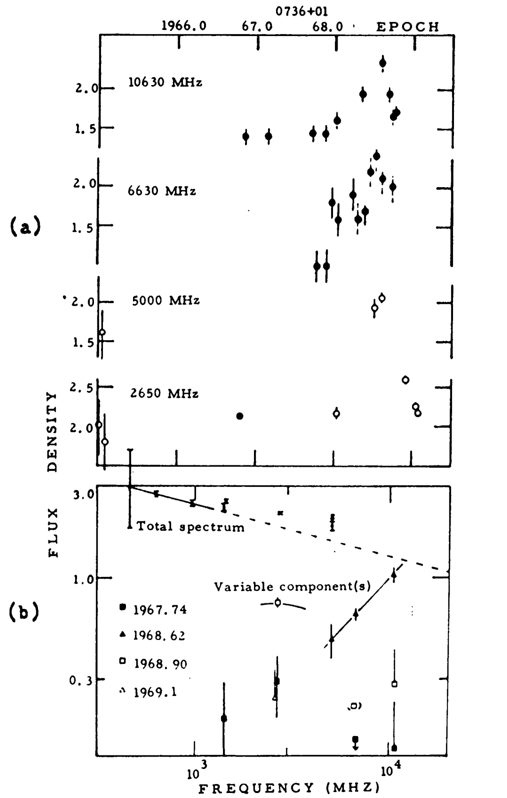

Fig. 5. The variable spectrum of the QSO, PKS 0736+01, showing (a) variations in flux density with epoch, for several frequencies (the open and closed circles have the same meaning as in Figure 4); (b) the total spectrum, and spectrum of the variable component at four epochs. The dashed line is an extrapolation of the low frequency spectrum, which was subtracted from the total spectrum at higher frequencies, to obtain the variable component.

at 5000, 6630 and 10630 MHz reached a maximum almost simultaneously, in conflict with the adiabatic expansion of an optically thick region. At this time, $\alpha = -1.0$ for the high frequency component indicating significant absorption. Although this high frequency component was barely detectable at 6630 and 10630 MHz in 1968.9 the source must have been optically thick at 2700 MHz until this time, after which the flux density rapidly decreased due to adiabatic relativistic expansion. The disappearance of the source at these frequencies by 1969.0 could be explained by relativistic expansion of an optically thin region. Locke *et al.* (1969) suggest that we have observed the birth of a variable component.

C. PKS 2345 – 16 (QSO)

Below 5000 MHz the variations are consistent with an expanding optically thick source, becoming optically thin above 2700 MHz at 1967.5 (Figure 6). At 5000 MHz

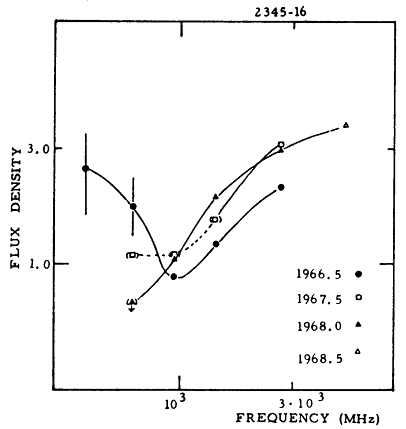

Fig. 6. The spectrum of the QSO, PKS 2345 – 16, at several epochs.

the flux density variations suggest continued injection of relativistic electrons. The very rapid decrease from 3.66 ± 0.07 to $3.46 \pm 0.07 \times 10^{-26}$ W m^{-2} Hz^{-1} between 1968.54 and 1968.60 (not shown) implies expansion velocities approaching that of light. These events may be compared with those in PKS 0736 + 01 and 1510 – 08, also the northern source NRAO 512 (Locke *et al.*, 1969).

The results of the analysis of 22 variable spectra show that, for the observed variable components:

(a) Ages range from a few months to more than 100 yr;

(b) The linear dimensions vary between ~0.1 pc and 100 pc;

(c) Relativistic expansion velocities are general, even if the QSOs are more local than implied by a cosmological interpretation of their redshifts. If the expansion is relativistic, energy requirements are reduced and possible inverse Compton catastrophes are avoided (Rees and Simon, 1968). Such high velocities appear to be necessary if the expanding synchrotron model is to explain the rapid variations of flux density observed in PKS 2251 + 15, 0736 + 01, 1510 – 08 and 2345 – 16.

(d) The derived angular sizes are in excellent agreement with those of very long baseline interferometry, if magnetic fields of 1 to 10^{-4} G are accepted. This agreement is independent of a cosmological interpretation of the redshifts.

Typical parameters for these young sources, obtained from the present study, are summarized in Table V. These are compared with the results of Colgate (1968) derived

TABLE V

Typical data derived for variable radio components

	Observed variable components[a]	Colgate's theory	
		Seyfert or N galaxy	QSO
Expansion age, t_0 (years)	1–100		
γ	1.0–1.5		
Expansion velocity (units of c)	0.03–0.9 (10^{-4}) 0.3–0.996 (1.)		
Linear size (pc)	0.5–20 (10^{-4}) 5–200 (1.)	$\sim$0.01–1	$\sim$0.01–1
Electron density (cm^{-3})	10^4–10^6 (10^{-4}) 0.1–10 (1.)		
Mass (relative to Sun)	$\sim 10^4$–10^6 (10^{-4}) ~ 1–10^2 (1.)	30–50	30–50
Rate of formation (yr^{-1})	~ 1	0.1–1	5–10
Internal energy (erg)	$\sim 10^{53}$ (relativistic expansion) $\sim 10^{58}$ (non-relativistic expansion)	10^{53}–10^{54}	10^{53}–10^{54}
Power output (erg s^{-1})	$\sim 10^{46}$ (non-relativistic expansion)	10^{45}–10^{46}	10^{46}–10^{47}

[a] Figure in parentheses is assumed magnetic field, in G.

from his theory of QSOs and related objects. The theory predicts a rapid succession of supernova events resulting from multiple stellar coalescence in a nucleus of 1 to 100 pc dimensions, containing $\sim 10^8$ to 10^{10} stars. This idea is particularly attractive in view of the approximately similar energies of variable components suggested by the observations, and that of a large supernova explosion (for example, Cas A). The observations of supernova remnants in the Galaxy suggest that an expanding shell and/or filamentary model may be more appropriate than the exploding uniform sphere fitted to the present observations. Woltjer (1966) has shown that energy requirements and inverse Compton losses in variable radio sources could then be reduced.

5. Conclusions

The QSOs, radio galaxies, and blank field objects may be distinguished statistically by their high frequency spectra. Above 1000 MHz, more than 30% of QSOs have flat spectra ($\alpha < 0.5$). The remaining QSOs have spectra similar to those of the radio galaxies. More than 30% of N and Seyfert galaxies (the most radio-luminous galaxies) also have flat spectra. The spectra of 15% of QSOs and 40% of radio galaxies show a definite increase in spectral index with increasing frequency. This steepening is even more marked in the case of blank field objects.

Near 100 MHz, 50% of the most luminous galaxies (N and faint galaxies) show synchrotron self-absorption compared with 25% for the remaining galaxies. This figure is 40% for QSOs and more than 50% for blank field objects.

Near 1000 MHz, a weak trend of increasing average spectral index with increasing luminosity is suggested.

The above results suggest that the blank field objects may be galaxies, more luminous at radio frequencies than those which are close enough to appear on the prints of the Palomar Sky Survey. Further evidence for this is provided by the fact that 60% of blank field objects show interplanetary scintillation, compared with 25% for galaxies. This may be attributed to their greater distance and also to the presence of compact components which, as is suggested by the above results, may be a characteristic of the most radio-luminous identified radio sources.

The detailed analyses of individual spectra bear out the above results. Although 'break' frequencies are observed in a few radio galaxies and one QSO, the increase in spectral index appears to be gradual in many other sources. This is particularly well illustrated by the spectra of the blank field objects.

Low percentage polarization at 2650 MHz is associated with QSOs having flat spectra; the QSOs with the steepest spectra have the highest percentage polarization at 2650 MHz. This result confirms that suggested by the observations of others and has been attributed to highly tangled magnetic fields within compact sources, which untangle as the source expands, resulting in a higher degree of integrated polarization.

Where sufficient radio observations are available, variability is suspected or confirmed for nearly all sources with flat spectra. Detailed analyses of variations of 22 individual spectra are consistent with the adiabatically expanding uniform source model of Shklovsky, Kellermann, van der Laan, and others. In the present investigation, in order to explain the rapid time variations it was necessary to introduce the modification suggested by Rees and Simon – namely that the expansion occurs with relativistic velocities.

The results of this study may be summarized as follows:

(a) Expansion ages are of the order of months to tens of years. The present observations were not designed to detect variations on time scales less than one or two months; but others to detect variations with time scales of days to months were also made (Harris, 1970c).

(b) Linear dimensions are between 0.1 and 100 pc.

(c) Comparison of the predicted angular dimensions with those measured by very long baseline interferometry suggests magnetic fields between 1 and 10^{-4} G in variable components.

(d) Relativistic expansion velocities are general, but are less for observed variable components of Seyfert galaxies than for QSOs.

(e) Observations of some variable components at frequencies of 5000 MHz and above suggest non-adiabatic expansion which may be the result of continued injection of energy into an expanding region.

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