OBSERVATIONS OF THE LINEAR POLARIZATION OF RADIO SOURCES AT 6 CM WAVELENGTH

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Summary

The polarizations of 45 sources have been measured at 6 cm wavelength and have been compared with values obtained at longer wavelengths. The resulting wavelength dependence has been studied in relation to the spectra of the sources. For the quasi-stellar objects in particular, polarization features at short wavelengths are associated with the young components of the source which radiate at high frequency. However, it is not possible to distinguish between radio galaxies and quasi-stellar objects solely on the basis of polarization data.

I. Introduction

Extensive observations of the linear polarization of radio sources have been carried out at wavelengths between 11 and 74 cm (Berge and Seielstad 1967; Gardner, Morris, and Whiteoak 1968; see also references to earlier papers in the review by Gardner and Whiteoak 1966). However, at wavelengths shorter than 11 cm the only extensive observations are those of Sastry, Pauliny-Toth, and Kellermann (1967) at 6 cm and Dent and Haddock (1966) at 3·75 cm.

The observations to be discussed here are the initial results of a programme to investigate the polarization of a larger sample of radio sources at short wavelengths and at southern declinations.

II. Observations

The observations were obtained with the Parkes 210 ft radio telescope in June and December 1966 and in March 1967. A few earlier observations had been made by Broten *et al.* (1965) and by F. F. Gardner (unpublished). The receiving equipment and methods of observation and reduction have been described previously (Morris, Whiteoak, and Tonking 1968). Summarizing, the receiver had an r.f. bandwidth of 200 MHz centred at 4995 MHz and a system noise temperature of about 900°K. For a time constant of 2 sec, the observed r.m.s. noise of the switched output was 0°·1. The 210 ft telescope was illuminated by a dual-mode primary feed and provided a beamwidth of 4′·1 to half-power points. Observations were made using the "on–off" technique at a series of feed orientations. The sequence at each feed angle generally consisted of a 50 sec observation 10′ west of the source, a 100 sec observation with the telescope tracking the source, and another observation of duration 50 sec at a position 10′ east of it. In this way changes of zenith angle during each sequence were minimized. The switched (i.e. polarized) and total power outputs were recorded on paper tape for subsequent reduction on a CDC 3200 computer. Their relative gains were

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established at each feed angle by the use of a calibration signal from a discharge tube. The observations were affected by instrumental polarization, which varied with feed orientation and zenith angle of the telescope. It was determined by the observation of several thermal radio sources over a range of zenith angle. The variation of the instrumental effect was almost sinusoidal with feed angle, and was approximated by a sinusoid of period 360° at each zenith angle. The amplitude of the correction varied from $1\cdot4\%$ at a zenith angle of 15° to $0\cdot6\%$ at 60°, attaining a minimum of $0\cdot5\%$ at 30°. The phase was reasonably constant at zenith angles less than 30° and at angles greater than 35°. However, between these limits the phase increased from 175° to 290°. It is believed that the variation is due to distortion of the dish at zenith angles greater than or less than 35°, at which position the surface has been adjusted to a parabolic figure. In view of the characteristics of the instrumental polarization, sources were generally observed at large zenith angles. Errors in telescope pointing were not significant since for each source the telescope was directed at the position where the total power was maximum. Thus for most sources the setting errors were less than $\pm 0'\cdot 5$. The basic calibration of the zero of the position angle scale was determined by radiating a linearly polarized signal from the apex of the telescope. Observations of the polarization of Jupiter during the December period (Morris, Whiteoak, and Tonking 1968) indicated an error of $5°\pm 1°$ in the calibration, and the results were adjusted accordingly.

The sources were selected from a list observed at longer wavelengths by Gardner, Morris, and Whiteoak (1968). Selection was confined to the brighter sources, or to fainter sources with appreciable polarization at 11 cm. Apart from the observation of several HII regions for the determination of instrumental polarization, a total of 45 objects was investigated. With a beamwidth of $4'\cdot 1$ it was possible to measure the polarization in the individual components of two of the sources (PKS 0518−45 and PKS 1322−42).

III. Results

The sources, their peak flux densities, percentage polarization, and directions of polarization are listed in Table 1. In addition to the Parkes nomenclature, alternative catalogue numbers are included. All errors quoted are standard deviations. The peak flux densities were obtained from the total power output of the receiver and have not been corrected for the effects of resolution. The intensity scale is based on a value of $13\cdot0$ f.u.* for PKS 0915−11 (Hydra A), as adopted by Kellermann (1966). As a result of instabilities in the total power output the accuracy of the flux densities is not high.

Twenty of the sources have also been observed by Sastry, Pauliny-Toth, and Kellermann (1967) with the NRAO 140 ft radio telescope. Excluding the source PKS 0430+05 (see later), the average differences in polarization ($\overline{\Delta p}$) and position angle ($\overline{\Delta \mathrm{P.A.}}$) are

$$\overline{\Delta p}(210-140) = -0\cdot2\% \pm 1\cdot2\% \text{ (r.m.s.)}, \qquad \overline{\Delta \mathrm{P.A.}}(210-140) = 3°\cdot7 \pm 5°\cdot5 \text{ (r.m.s.)}.$$

The scatter about the mean values has probably been enhanced by the partial resolution of some of the sources by the 210 ft telescope, since most extended sources

* 1 flux unit $= 10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$.

TABLE 1

LINEAR POLARIZATION AT 6 CM

Parkes Catalogue Number	Alternative Catalogue Number	Peak Flux Density (f.u.)	Linear Polarization (%)	Position Angle °
PKS 0106+13	3C 33	2·9	8·2±0·8	94±7
0356+10	3C 98	3·3	6·5±1·5	80±3
0410−75	MSH 04−7*1*	4·5	1·7±0·4	40±4
0430+05	3C 120	7·0	1·3±0·3	13±12
0438−43	MSH 04−4*9*	6·1	2·0±1·0	45±15
0440−00		3·5	2·5±1·5	30±10
0518+16	3C 138	4·2	8·9±1·0	169±4
0518−45(NW.)	Pictor A	11·2	8·8±0·7	124±3
0518−45(SE.)		10·0	6·5±1·2	81±5
0521−36	MSH 05−3*6*	8·6	3·0±0·5	69±6
0531+22	3C 144	>450	5·6±0·1	141±1
0539−01	3C 147	38	0·2±0·2	165±12
0624−05	3C 161	7·0	4·1±0·6	122±3
0637−75	MSH 06−7*1*	5·3	1·4±1·0	179±15
0915−11	3C 218	13·0	<0·5	
1055+01	MSH 10+0*10*	3·2	4·3±1·0	94±7
1127−14		6·7	3·1±1·0	132±6
1216+06	3C 270	4·1	10·8±0·9	94±2
1226+02	3C 273	43	2·0±0·3	150±3
1228+12	3C 274	64	2·0±0·1	26±1
1252−12	3C 278	2·4	8·0±3·0	13±15
1253−05	3C 279	14·6	4·3±0·4	110±3
1302−49	MSH 13−4*1*	2·4	4·5±2·5	165±15
1322−42(W.)	Centaurus A (central component)	43	1·9±0·2	96±2
1322−42(E.)		54	16·3±0·3	139±2
1323−61		3·5	4·7±1·0	45±5
1328+25	3C 287	2·9	6·4±1·8	154±10
1343−60	13S6A	9·1	8·9±0·3	41±1
1549−79		3·3	3·5±1·0	114±5
1610−60	MSH 16−6*1*	4·7	5·0±1·0	4±6
1610−77		3·3	7·1±2·2	104±6
1648+05	3C 348	11·3	7·0±0·9	25±3
1717−00	3C 353	17·3	6·2±0·5	85±3
1727−21	3C 358	5·7	1·6±1·0	103±20
1737−30	MSH 17−3*9*	8·7	2·5±0·6	27±7
1742−28	Sagittarius A	>126	0·8±0·5	164±20
1814−46	HII region		1·6±1·0	170±15
1814−63	MSH 18−6*1*	4·4	2·4±0·8	37±12
1932−46	MSH 19−4*6*		<1·5	
1934−63		6·0	<0·5	
2121+24	3C 433	3·9	3·9±1·0	144±5
2145+06		4·2	2·0±2·0	42±20
2152−69	MSH 21−6*4*	10·8	1·3±0·6	30±10
2223−05	3C 446	3·9	4·4±1·0	3±10
2230+11	CTA 102	4·0	5·5±0·6	47±6
2251+15	3C 454·3	17·5	1·8±0·3	3±7
2356−61	MSH 23−6*4*	4·1	3·4±0·9	177±10

are characterized by variations of polarized flux and position angle across their diameters. In addition, for quasi-stellar objects there may have been variations in the parameters in the period between the two sets of observations. However, on the basis of the present results, there appears to be a systematic difference in the position angle scales of 4°.

The data for sources with significant polarization are shown in Figures 1–3, together with observations at longer wavelengths (Gardner, Morris, and Whiteoak 1968). The sources have been grouped into radio galaxies, quasi-stellar objects, and galactic and unidentified objects, according to the identifications compiled in Gardner, Morris, and Whiteoak. On the left-hand side of each figure is shown the relationship between percentage polarization and the square of the wavelength. The continuous lines represent the approximate trends in the observations. The right-hand side of each figure contains the variation of log(flux density) with log(frequency). The variations of direction of polarization with the square of the wavelength are not shown as they are linear for most sources and more likely to be associated with our Galaxy than to be indigenous to the sources (Gardner and Whiteoak 1966). Sources showing departures from linearity will be discussed individually. The characteristics of the intrinsic angles of polarization are discussed in Gardner, Morris, and Whiteoak.

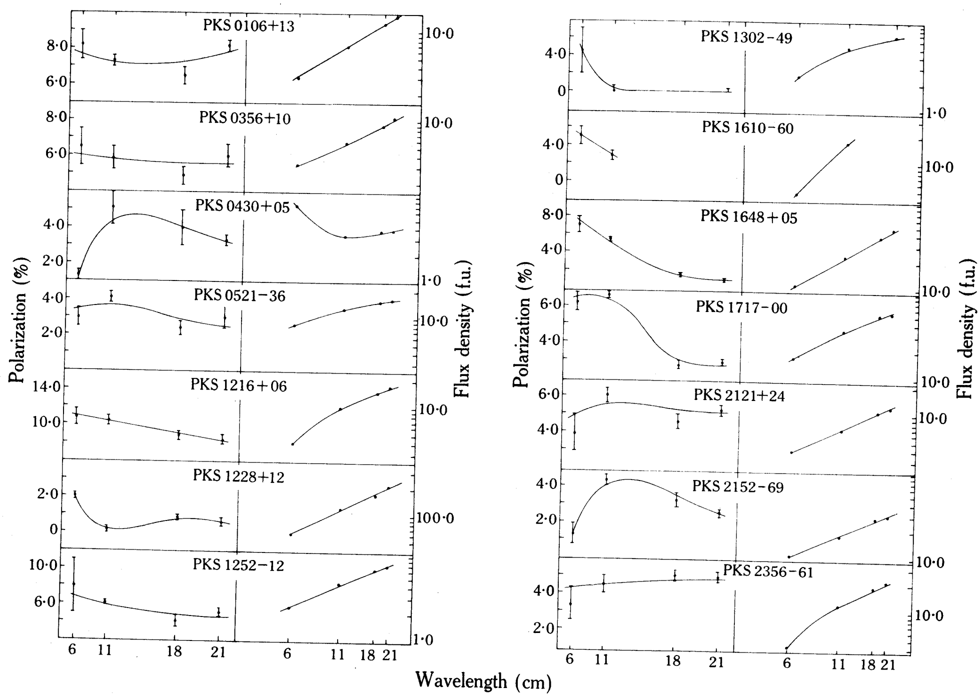
(a) *Radio Galaxies*

The radio sources identified with galaxies are shown in Figure 1. For each, the identification, its magnitude, and radio dimensions are given in the accompanying table. The component separation is designated Sep. for double sources, and the halo and core estimates for sources with more complex structure are followed by H and C respectively. The data are from the compilation of Gardner, Morris, and Whiteoak (1968). Because of the lack of corresponding data at longer wavelengths, the resolved sources PKS 0518−45 and PKS 1322−42 have been excluded.

The sources associated with D and E galaxies and with simple single or double radio structure have linear spectra except in the cases where obvious resolution effects are present at 6 cm (PKS 1216+06, PKS 1302−49, PKS 1610−60, PKS 1717−00, and PKS 2356−61). Their spectral indices are quite similar at wavelengths longer than 11 cm. The percentage polarization is relatively constant except for PKS 2152−69 and for the objects of greater brightness temperature, namely, PKS 1648+05 and PKS 1717−00, where the substantial decrease of polarization with increasing wavelength suggests the presence of internal Faraday depolarization. The interpretation of the structure of PKS 2152−69, and possibly its optical identification, are open to doubt, as Ekers (1967) has pointed out. One of the components is seven times fainter than the other at 1400 MHz and has a significantly steeper spectral index, and the source cannot be considered a typical double source. Moreover, it is difficult to interpret the polarization relationship merely by the association of the polarization with the source having the steeper spectral index, or by the presence of internal Faraday depolarization.

For the two halo–core objects PKS 1228+12 and PKS 1302−49, the rapid increase of percentage polarization at 6 cm could occur if the polarization were associated with the core of the objects, since in each case the halo is extensively resolved at this wavelength.

The source PKS 0430+05 is identified with a Seyfert-type galaxy. At least some of the radio emission emanates from a region of $\leqslant 0''\cdot 1$ as the radiation scintillates at a sufficiently small elongation from the Sun. At high frequencies the radiation



Source	Optical Identification	Radio Dimen. (min of arc)	Source	Optical Identification	Radio Dimen. (min of arc)
PKS 0106+13	$15\cdot 6^m$D	Sep. 3·8	PKS 1302−49	9^m Sc	{9·0×4·5H <0·5C
PKS 0356+10	$15\cdot 0^m$E	Sep. 3·4	PKS 1610−60	$12\cdot 8^m$E	6·0
PKS 0430+05	$15\cdot 0^m$Sey.	$<10^{-3}$	PKS 1648+05	$18\cdot 3^m$D	Sep. 2·0
PKS 0521−36	$16\cdot 8^m$N	<0·3	PKS 1717−00	$16\cdot 8^m$D	Sep. 2·5
PKS 1216+06	$12\cdot 0^m$E	Sep. 4·7	PKS 2121+24	17^m D	{Sep. 0·2 (at P.A. 67°)
PKS 1228+12	$9\cdot 9^m$E	6·6H, $<10^{-3}$C	PKS 2152−69	$13\cdot 8^m$D	Sep. 3·8
PKS 1252−12	$13\cdot 5^m+13\cdot 2^m$	{1·5 (at P.A. 90°)	PKS 2356−61	16^m D	Sep. 4·0, 8·1

Fig. 1.—Variation of percentage polarization with (wavelength)^2 together with corresponding spectral information (log–log scale) for radio sources identified with galaxies.

is variable (Pauliny-Toth and Kellermann 1966). The shape of the spectrum shown may not be that existing at the time at which the 6 cm observations were obtained, since the data for longer wavelengths were determined at different epochs. However, the general shape conforms to the two-component model proposed for the radiation of quasi-stellar objects (Pauliny-Toth and Kellermann 1966; Harris 1967). In this model the high frequency component originates in a young compact region. For PKS 0430+05 most of the polarization at 6 cm is probably associated with the low frequency component, the small percentage being due to the addition of unpolarized radiation from the variable high frequency component. Also, the polarized flux density is independent of the intensity variations of this second component. In this respect, Sastry, Pauliny-Toth, and Kellermann (1967) list a total flux density only half the value measured in the present observations, and a percentage polarization that is approximately double that shown in Figure 1. However, it appears that the high frequency component must be polarized to a certain extent, but with a different direction of polarization, to account for a 30° difference between the observed angle at 6 cm and the value extrapolated from observations at longer wavelengths.

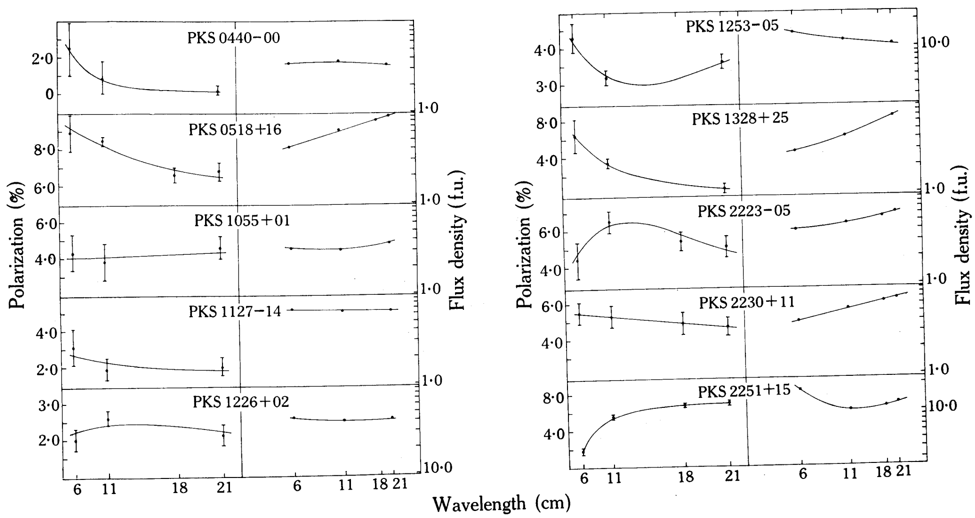


Fig. 2.—Variation of percentage polarization with (wavelength)^2 together with corresponding spectral information (log–log scale) for quasi-stellar sources.

The source PKS 0521−36, associated with an N-type galaxy, is characterized by a flatter spectrum than average. It may represent an object of a type between the normal radio galaxy and PKS 0430+05.

(*b*) *Quasi-stellar Objects*

The quasi-stellar objects (Fig. 2) show a variety of features. Most of the spectra differ considerably from those observed for radio galaxies. The differences are due in many cases to the presence of a high frequency component of radiation that vanishes at decimetre wavelengths because of synchrotron self-absorption. For the sources PKS 2223−05 and PKS 2251+15 the polarization appears to be associated predominantly with the low frequency component, showing a decrease at 6 cm. For such cases, the high frequency component may be essentially unpolarized at 6 cm. This could occur if it were optically thick, or in the presence of sufficiently large values of internal Faraday rotation. The sources PKS 0518+16 and PKS 1328+25 have the characteristics of highly luminous radio galaxies such as PKS 1648+05 and may lack a significant high frequency component. The extensive depolarization suggests the presence of differential Faraday rotation. Although it is not evident in the present results, observations of PKS 1226+02 by Aller and Haddock (1967) at 3·75 cm imply an association of the polarization with the varying (i.e. high frequency) component.

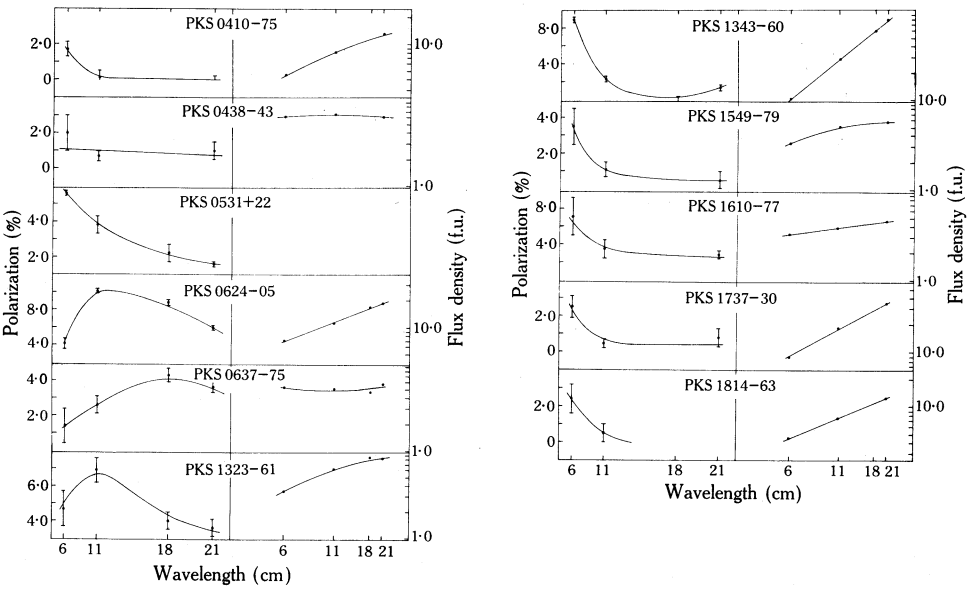


Fig. 3.—Variation of percentage polarization with (wavelength)^2 together with corresponding spectral information (log–log scale) for galactic and unidentified sources:

PKS 0410−75, <0·4′;	PKS 1343−60, galactic;
PKS 0438−43, <0·3′ (at P.A. 90°);	PKS 1549−79, <0·4′;
PKS 0531+22, Crab Nebula;	PKS 1737−30, galactic;
PKS 0624−05, <0·03′ (at P.A. 67°);	PKS 1814−63 <0·4′.
PKS 0637−75, <0·3′.	

Of the remainder, PKS 1127−14 and PKS 1253−05 are outstanding owing to a nonlinear relationship between Faraday rotation and (wavelength)^2. A simple interpretation is that both the components of radiation are polarized but in different directions. In particular, PKS 1253−05 has a position angle of polarization at 6 cm that differs by 20° from the value to be expected by extrapolation from longer wavelengths. The shift is towards the value determined by Kinman (1967) for the optical radiation. The polarization of this source at 3·75 cm has been observed over a considerable period of time by Aller and Haddock (1967) and shows short-period fluctuations.

(c) *Unidentified and Galactic Objects*

The results for the unidentified and galactic sources are shown in Figure 3. The galactic sources consist of PKS 0531+22 (Crab Nebula), PKS 1343−60, and possibly PKS 1737−30. A fourth source listed in Table 1, PKS 1727−21 (Kepler's Nova), is virtually unpolarized at all frequencies employed. The source PKS 1343−60 is an extended object ($> 10'$), the resolution of which probably accounts for the apparently steep spectrum. It is of particular interest, as it lies within a few degrees of the recently determined position of the variable X-ray source Cen XR-2 (Francey *et al.* 1967), and an association between the two objects is not currently out of the question. The apparent depolarization for these galactic sources may be due to differential internal Faraday rotation or, in the case of PKS 1343−60, to the concentration of polarization into a region of small angular size.

The sources PKS 0624−05, PKS 0637−75, and PKS 1323−61 have the polarization features characteristic of objects with a high frequency component of radiation, as exemplified by some quasi-stellar objects or intermediate objects such as PKS 0430+05. In contrast, PKS 0438−43, PKS 1549−79, and PKS 1610−77 have characteristics similar to quasi-stellar objects such as PKS 2230+11 or the N-type galaxy PKS 0521−36. The remaining sources are probably of high luminosity and associated with faint D galaxies.

IV. Conclusions

The polarization measurements at 6 cm have brought to light a number of features in the variation of polarization with wavelength that are not present at longer wavelengths. For the quasi-stellar objects the short-wave dependence of polarization on wavelength can in many cases be associated with features in the spectrum. These features have usually been attributed to the presence of young compact components. In some cases, there is evidence that the radiation from these components is polarized. In others, the high optical depths of the radiation at 6 cm may be responsible for the observed low polarization. However, it is not possible to distinguish all quasi-stellar objects from radio galaxies on the basis of their short-wave polarization properties alone.

V. Acknowledgments

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VI. References

Aller, H. D., and Haddock, F. T. (1967).—*Astrophys. J.* **147**, 833.

Berge, G. L., and Seielstad, G. A. S. (1967).—*Astrophys. J.* **148**, 367.

Broten, N. W., *et al.* (1965).—*Aust. J. Phys.* **18**, 85.

Dent., W. A, and Haddock, F. T. (1966).—*Astrophys. J.* **144**, 568.

Ekers, R. D. (1967).—Ph.D. Thesis, Australian National University.

Francey, R. J., Fenton, A. G., Harries, J. R., and McCracken, K. G. (1967).—*Nature, Lond.* **216**, 773.

Gardner, F. F., Morris, D., and Whiteoak, J. B. (1968).—Measurements of the linear polarization of radio sources between 11 and 20 cm. *Aust. J. Phys.* (in press).

Gardner, F. F., and Whiteoak, J. B. (1966).—*A. Rev. Astr. Astrophys.* **4**, 245.

Harris, B. J. (1967).—*Publs astr. Soc. Aust.* **1**, 26.

Kellermann, K. I. (1966).—*Aust. J. Phys.* **19**, 577.

Kinman, T. D. (1967).—*Astrophys. J. Lett.* **148**, L53.

Morris, D., Whiteoak, J. B., and Tonking, F. G. (1968).—*Aust. J. Phys.* **21**, 337.

Pauliny-Toth, I. I. K., and Kellermann, K. I. (1966).—*Astrophys. J.* **146**, 634.

Sastry, Ch. V., Pauliny-Toth, I. I. K., and Kellermann, K. I. (1967).—*Astr. J.* **72**, 234.