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# Flux Densities, Spectra and Variability of Pulsars at Metre Wavelengths

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*Abstract*

We present the results of two-frequency flux density measurements of 74 pulsars with the Culgoora circular array. We show that the spectral index of a typical pulsar steepens markedly from 80 to 1400 MHz, but we found no significant relationship between the metre-wave spectral index and the published pulsar parameters.

We investigated the intensity changes in 22 pulsars at 160 MHz over an 18-month interval and found that 19 of them were variable on a month-to-month time scale. A search for relationships between the degree of variability and the published pulsar parameters showed a highly significant dependence on dispersion measure and a probable dependence on period derivative. We attribute the dependence on dispersion measure to slow scintillations caused by large-scale turbulence in the interstellar medium, although the high amplitude of the intensity changes is not consistent with a recently proposed model for slow interstellar scintillation. The dependence of variability on period derivative and a high degree of correlation between intensity changes at 80 and 160 MHz demonstrate the presence of an intrinsic variability component.

## 1. Introduction

Reliable measurements of pulsar fluxes are difficult to obtain because of the operation of a number of processes which modulate the intensity either at the source or in the intervening medium. In addition, most of the existing measurements have been made at frequencies >300 MHz, where the large single reflectors and cross-type telescopes operate most efficiently. As a result there have not been any comprehensive measurements of pulsar fluxes at metre wavelengths, where there may be as yet undiscovered clues to the generating mechanism and additional propagation effects in the pulsar atmosphere and interstellar medium.

It is difficult to construct believable low-frequency pulsar spectra from sporadic measurements at single frequencies when it is known that: (i) interstellar scintillations on time scales of a few minutes to hours are correlated over at most 1 or 2 MHz; (ii) there may be slower interstellar scintillations with time scales of months (Sieber 1982); (iii) intrinsic intensity changes at the pulsar may occur on all time scales.

The present investigation attempts to address at least some of these problems by using the results of two-frequency pulsar observations with the Culgoora circular array (CCA) from April 1979 to November 1980.

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In Section 2 we describe the observational procedure and subsequent reductions. Section 3 gives the results of two-frequency flux density measurements of 74 pulsars, presents the metre-wave spectra of the detected pulsars and relates them to their measured high-frequency spectra. Section 4 presents our analysis of the month-to-month variability in our metre-wave data and in Section 5 we summarize the results and discuss their implications.

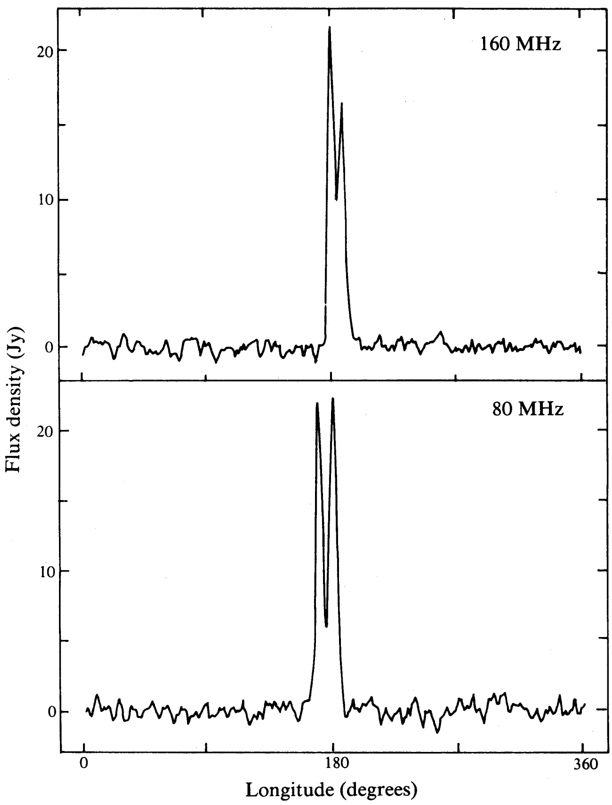


**Fig. 1.** Averaged simultaneous pulse profiles of PSR 1133+16 at 80 and 160 MHz. The output of a filter bank with instantaneous bandwidth of 90 kHz and total bandwidth of 880 kHz has been sampled at 7·8 ms intervals for 30 min. The apparent displacement between the 80 and 160 MHz profiles is due to the alignment of the peak of the profile at the centre of the folded period.

## 2. Observations and Reductions

The method of using the CCA for pulsar observations has been described by Slee *et al.* (1980). Here it is sufficient to state that for pulsed flux measurements the outputs of a 9×90 kHz bandwidth filter bank occupying a total bandwidth of 880 kHz centred on 80 or 160 MHz were added and sampled at 7·8 ms intervals. The data were folded at the apparent pulse period, integrated for 60 s and recorded on tape for further off-line analysis. In the first observation of a pulsar our normal procedure was to observe at 80 and 160 MHz (beamwidths 3′·8 and 1′·9 arc respectively) on successive

60 s integrations with the total observation extending over 1 h. After checking the individual 60 s integrations for interference, the 30 integrations at each frequency were added to produce averaged pulse profiles for the observing session. It is clear that such a procedure minimizes the effect of recognized interstellar scintillations on flux measurements: at metre wavelengths the correlation bandwidths are typically a few tens of kHz whereas we were averaging over 880 kHz, and the scintillation timescales are 2 or 3 min whereas we were averaging over 30 min. In addition, the almost simultaneous recording at 80 and 160 MHz ensured that any broadband intrinsic variability would not invalidate the measurement of the instantaneous spectrum.

Fig. 1 shows the quasi-simultaneous averaged pulse profiles of **PSR** 1133+16 at 80 and 160 MHz. The flux scale of these recordings was calibrated by observing strong unresolved extragalactic radio sources at intervals of a few hours during the night. In order to simulate a pulsar, the radio beam was scanned across the calibrator once each second and the outputs of the filter bank were processed in the manner as for pulsar observations.

If we discovered that pulsar emission could not be detected at one or the other frequency (usually at 80 MHz because of higher system noise and/or pulse smearing due to interstellar scattering), further observation of that pulsar was confined to the detected frequency; such a procedure maximized the signal-to-noise ratio in the available time and thus improved the accuracy of the flux measurement.

## 3. Measurements of Pulsed Flux Density and Spectra

Table 1 summarizes our measurements of pulsed flux at 80 and 160 MHz. If pulses were detected we give the median pulsed flux density; if no pulses were detected we give the $3\sigma$ upper limit. The upper limits were computed assuming that the equivalent width of the pulse is equal to its high-frequency value as listed by Manchester and Taylor (1981) and may seriously underestimate the pulsed fluxes if the pulses were appreciably widened by interstellar scattering; the latter circumstance would certainly apply at 80 MHz to most of the pulsars with dispersion measures $\geqslant 50\ \mathrm{cm}^{-3}\,\mathrm{pc}$. We also list in Table 1 the 400 and 1400 MHz values of pulsed flux density given by Manchester and Taylor (1981), together with the spectral indices for various ranges of frequency; the latter were computed assuming a power law variation of the form $S(\nu) \propto \nu^{\alpha}$ between the indicated frequencies of observation.

Fig. 2 shows the three distributions of spectral index of those 27 pulsars for which 80 and 160 MHz fluxes were simultaneously recorded. It is clear that the spectral index of a typical pulsar steepens markedly and progressively from 80 to 1400 MHz; the Kruskal–Wallis ranking coefficient (Hughes and Grawoig 1971) for testing whether distributions are likely to have been drawn from the same population indicates that the probability of this is $<0\cdot001$.

It is of interest to test the data for consistent differences between the metre-wave spectra of pulsars. We have compared the distributions of instantaneous $\alpha_{80}^{160}$ for the five pulsars (0919+06, 0950+08, 1133+16, 1604−00, 1642−03) having at least five measurements. A Kruskal–Wallis ranking test showed that these distributions (with median $\alpha_{80}^{160}$ ranging between $+0\cdot01$ and $-0\cdot80$) were highly likely to have been drawn from the same population. Even the ranking coefficient for the two pulsars with the extreme medians was not indicative of a spectral difference at the 95% confidence level. The above investigation does not deny that some pulsars may possess metre-wave spectral indices that consistently depart from the median

**Table 1. Measurements of median pulsed flux**

| Pulsar | No. of measurements[A] 80 MHz | No. of measurements[A] 160 MHz | Median pulsed flux (mJy) 80 MHz | Median pulsed flux (mJy) 160 MHz | High frequency pulsed flux (mJy)[B] 400 MHz | High frequency pulsed flux (mJy)[B] 1400 MHz | Spectral indices $\alpha_{80}^{160}$ | Spectral indices $\alpha_{160}^{400}$ | Spectral indices $\alpha_{400}^{1400}$ |
|---|---|---|---|---|---|---|---|---|---|
| 0031−07 | 4 | 3 | 1000 | 310 | 25 | 10 | −1·70 | −2·75 | −0·73 |
| 0149−16 | 2 | 2 | 250 | 150 | 21 | | −0·76 | −2·12 | |
| 0203−40 | 0 | 1 | — | <30 | 11 | | | >−0·81 | |
| 0301+19 | 3 | 2 | 70 | 80 | 28 | | +0·15 | −1·13 | |
| 0450−18 | 3 | 4 | <60 | 100 | 55 | 47 | >+0·73 | −0·63 | −0·13 |
| 0540+23 | 2 | 3 | <30 | <20 | 30 | | — | >+0·69 | |
| 0611+22 | 3 | 4 | <20 | <20 | 25 | | — | >+0·24 | |
| 0628−28 | 4 | 2 | 530 | 90 | 90 | 13 | −2·52 | −0·04 | −1·54 |
| 0736−40 | 0 | 2 | — | <30 | 190 | 80 | | >+2·05 | −0·69 |
| 0740−28 | 1 | 5 | <20 | 240 | 195 | 25 | >+3·99 | −0·22 | −1·64 |
| 0818−13 | 2 | 3 | 170 | 100 | 90 | | −0·73 | −0·13 | |
| 0820+02 | 1 | 1 | <70 | <30 | 22 | | — | >−0·30 | |
| 0823+26 | 2 | 2 | 670 | 240 | 70 | 21 | −1·46 | −1·36 | −0·96 |
| 0826−34 | 1 | 1 | <70 | <40 | 16 | | — | >−1·03 | |
| 0833−45 | 0 | 3 | — | 1800 | 5000 | 1100 | | +1·13 | −1·21 |
| 0834+06 | 3 | 3 | 480 | 370 | 65 | 7 | −0·37 | −1·91 | −1·78 |
| 0835−41 | 3 | 5 | <30 | 100 | 197 | 25 | >+2·21 | +0·72 | −1·65 |
| 0844−35 | 0 | 1 | — | <20 | 16 | | | >+0·07 | |
| 0919+06 | 5 | 5 | 360 | 240 | 40 | | −0·61 | −1·94 | |
| 0943+10 | 5 | 2 | 440 | 80 | 15 | | −2·39 | −1·87 | |
| 0950−38 | 0 | 2 | — | <50 | 8·5 | | | >−1·96 | |
| 0950+08 | 6 | 6 | 3300 | 2500 | 900 | 140 | −0·42 | −1·12 | −1·49 |
| 1114−41 | 3 | 3 | 150 | 120 | 26 | | −0·32 | −1·70 | |
| 1133+16 | 8 | 9 | 540 | 440 | 340 | 70 | −0·28 | −0·28 | −1·26 |
| 1237+25 | 5 | 8 | 150 | 150 | 160 | 14 | +0·02 | +0·09 | −1·94 |
| 1237−41 | 2 | 3 | <50 | <30 | 3·5 | | — | >−2·14 | |
| 1325−43 | 3 | 4 | <130 | <40 | 18 | | — | >−0·79 | |
| 1504−43 | 1 | 3 | <60 | <30 | 16 | | — | >−0·53 | |
| 1507−44 | 2 | 2 | <340 | <100 | 14 | | — | >−2·16 | |
| 1524−39 | 2 | 2 | <130 | 50 | 11 | | >−1·46 | −1·58 | |
| 1541+09 | 7 | 7 | 480 | 250 | 100 | | −0·97 | −0·99 | |
| 1556−44 | 1 | 3 | <30 | <30 | 110 | 16 | — | >+1·66 | −1·54 |
| 1604−00 | 5 | 6 | 430 | 240 | 45 | | −0·81 | −1·85 | |
| 1612+07 | 0 | 2 | — | <30 | 12 | | | >−0·76 | |
| 1642−03 | 9 | 7 | 510 | 610 | 300 | 30 | +0·25 | −0·77 | −1·84 |
| 1700−32 | 1 | 1 | <240 | <90 | 45 | 6 | — | >−0·69 | −1·61 |
| 1706−16 | 8 | 4 | 310 | 180 | 60 | 20 | −0·79 | −1·21 | −0·88 |
| 1719−37 | 1 | 1 | <100 | <50 | 25 | | — | >−0·67 | |

**Table 1. (*Continued*)**

| Pulsar | No. of measurements[A] 80 MHz | No. of measurements[A] 160 MHz | Median pulsed flux (mJy) 80 MHz | Median pulsed flux (mJy) 160 MHz | High frequency pulsed flux (mJy)[B] 400 MHz | High frequency pulsed flux (mJy)[B] 1400 MHz | Spectral indices $\alpha_{80}^{160}$ | Spectral indices $\alpha_{160}^{400}$ | Spectral indices $\alpha_{400}^{1400}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1737−39 | 0 | 2 | — | <30 | 35 | | | >+0·13 | |
| 1738−08 | 0 | 1 | — | <60 | 40 | | | >−0·44 | |
| 1742−30 | 2 | 2 | <80 | <60 | 55 | | — | >−0·02 | |
| 1749−28 | 6 | 4 | 1800 | 2500 | 1300 | 16 | +0·52 | −0·73 | −3·51 |
| 1804−08 | 2 | 3 | <90 | <30 | 55 | | — | >+0·90 | |
| 1813−36 | 1 | 3 | <100 | <40 | 22 | | — | >−0·48 | |
| 1818−04 | 2 | 5 | <70 | 540 | 170 | 12 | >+3·05 | −1·26 | −2·12 |
| 1821−19 | 2 | 2 | <300 | <270 | 52 | | — | >−1·79 | |
| 1821+05 | 0 | 1 | — | 120 | 25 | | | −1·71 | |
| 1822−09 | 1 | 1 | 360 | 100 | 32 | 9 | −1·83 | −1·71 | −1·01 |
| 1842+14 | 0 | 1 | — | 160 | 30 | | | −1·81 | |
| 1844−04 | 0 | 4 | — | <50 | 100 | | | >+0·80 | |
| 1845−01 | 0 | 1 | — | <40 | 60 | 10 | | >+0·47 | −1·43 |
| 1857−26 | 3 | 3 | 870 | 260 | 120 | 10 | −1·72 | −0·86 | −1·98 |
| 1859+03 | 0 | 1 | — | <60 | 125 | 6 | | >+0·90 | −2·42 |
| 1900+01 | 1 | 3 | <70 | <40 | 60 | 2 | — | >+0·42 | −2·71 |
| 1907+10 | 2 | 3 | <30 | 110 | 55 | | >+1·87 | −0·76 | |
| 1907+02 | 0 | 1 | — | 60 | 20 | | | −1·10 | |
| 1910+20 | 1 | 2 | <50 | <20 | 10 | | — | >−0·20 | |
| 1911−04 | 4 | 4 | <30 | 180 | 120 | 4 | >+2·84 | −0·44 | −2·71 |
| 1915+13 | 1 | 5 | <30 | 180 | 30 | 5 | >+2·95 | −1·94 | −1·43 |
| 1917+00 | 1 | 2 | <80 | <20 | 30 | | – | >+0·56 | |
| 1919+21 | 2 | 4 | 750 | 1300 | 240 | 6 | +0·79 | −1·84 | −2·94 |
| 1920+21 | 0 | 3 | — | 170 | 45 | | | −1·42 | |
| 1929+10 | 2 | 2 | 430 | 710 | 130 | 35 | +0·73 | −1·86 | −1·05 |
| 1933+16 | 1 | 3 | <40 | 270 | 260 | 25 | >+2·96 | −0·02 | −1·87 |
| 1940−12 | 0 | 3 | — | 70 | 15 | | | −1·74 | |
| 1944+17 | 0 | 1 | — | 50 | 60 | 12 | | +0·22 | −1·28 |
| 1946+35 | 0 | 2 | — | <30 | 120 | | | >+1·44 | |
| 2002+31 | 0 | 1 | — | <20 | 14 | | | >−0·08 | |
| 2016+28 | 2 | 4 | 280 | 290 | 150 | 12 | +0·04 | −0·70 | −2·02 |
| 2020+28 | 6 | 6 | <40 | 210 | 250 | 38 | >+2·56 | +0·08 | −1·50 |
| 2028+22 | 1 | 1 | 70 | 40 | 5 | | −0·74 | −2·32 | |
| 2045−16 | 3 | 4 | 340 | 160 | 130 | 9 | −1·15 | −0·19 | −2·13 |
| 2303+30 | 2 | 3 | 60 | 40 | 25 | | −0·54 | −0·57 | |
| 2327−20 | 1 | 1 | 250 | 100 | 19 | | −1·36 | −1·80 | |

[A] These include all measurements whether or not made simultaneously at the two frequencies. The resulting $\alpha_{80}^{160}$ values in column 8, computed from the median fluxes, may differ in some pulsars from their median instantaneous spectral indices that are discussed in Section 3.

[B] From Manchester and Taylor (1981).

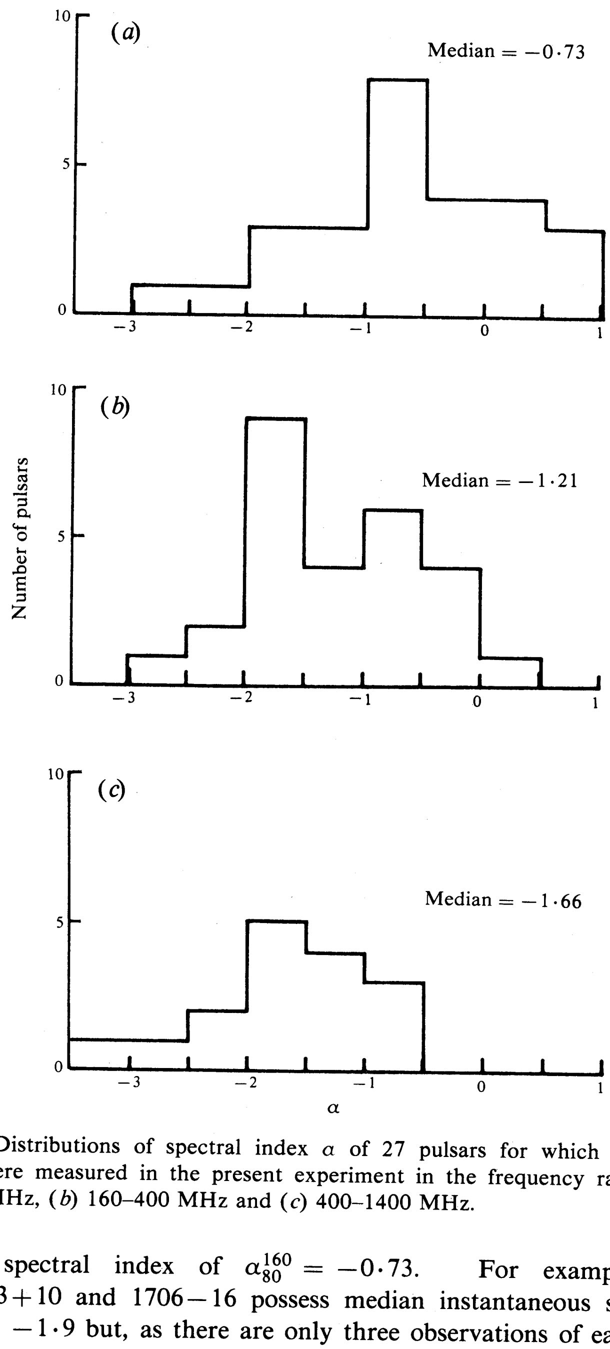


**Fig. 2.** Distributions of spectral index $\alpha$ of 27 pulsars for which the $\alpha_{80}^{160}$ values were measured in the present experiment in the frequency ranges (*a*) 80–160 MHz, (*b*) 160–400 MHz and (*c*) 400–1400 MHz.

instantaneous spectral index of $\alpha_{80}^{160} = -0{\cdot}73$. For example, 0031−07, 0628−28, 0943+10 and 1706−16 possess median instantaneous spectral indices $-2{\cdot}9 < \alpha_{80}^{160} < -1{\cdot}9$ but, as there are only three observations of each pulsar, it is difficult to show conclusively that they possess abnormally steep spectra. Nevertheless, in view of the fact that the standard error in each individual value of spectral index is $<0{\cdot}4$ one suspects that their spectra are abnormally steep.

We have searched the data for relationships between the median instantaneous spectral indices and measured and derived pulsar properties. This was done by constructing scatter plots backed up by the computation of linear and quadratic regression equations. No significant relationship was found between spectral index and pulsar distance, dispersion measure, period, period derivative, timing-age, radio luminosity, and surface magnetic field. The data of Manchester and Taylor (1981) were used in this investigation.

## 4. Temporal Flux Variations

Many of the pulsars in our list were observed often enough to permit a search for intensity changes over the 18-month interval covered by our measurements. The pulsars were not observed frequently enough for us to examine the day-to-day variability but sufficient measurements were made to study the temporal variability on time scales of a month or more.

The variability study was based on a chi-squared analysis defined by the equation

$$\chi^2 = \sum_{i=1}^{i=n} \frac{(S_i - \overline{S})^2}{\epsilon_i^2},$$

where $S_i$ is the measured monthly value of pulsed flux (an average being taken if there is more than one measurement within 30 days), $\overline{S}$ is the overall averaged pulsed flux of the pulsar and $\epsilon_i$ is the standard error in $S_i$; $\epsilon_i$ is the quadrature sum of a fixed percentage error due to calibration uncertainties and a variable percentage error due to system noise. The calibration component of error (10·0%) was derived from the average scatter in the calibrator source amplitudes within and between the 14 observing sessions. The noise component of error varied between 1% and 35% of pulsed flux and was estimated from a computer simulation in which gaussian-shaped pulses of varying width and amplitude were added to many independent samples of random noise.

Table 2 lists values of reduced chi-squared $[\chi^2/(n-1)]$, where $n$ is the number of flux measurements. The expectation value of $\chi^2/(n-1)$ is 1 and the significance of any deviation from 1 depends upon the number of degrees of freedom $(n-1)$; for example, with a typical number of four measurements $\chi^2/(n-1) \geqslant 2{\cdot}6$ would be exceeded by chance in 5% of trials and $\chi^2/(n-1) \geqslant 3{\cdot}8$ in 1% of trials. It is clear that practically all these pulsars vary significantly at one or both frequencies on a time scale of months—the only apparent exceptions are 0450−18, 1114−41 and 1933+16.

In order to obtain a variability parameter that can be used for further quantitative statistical comparisons we have computed a modulation index $m$ defined by

$$m = \left(\sum_{i=1}^{i=n} (S_i - \overline{S})^2 \Big/ n\right)^{\frac{1}{2}} \overline{S}^{-1},$$

which is the r.m.s. deviation of the individual flux measurements from the averaged pulsed flux divided by the averaged pulsed flux. The values of $m$ are given in Table 2. Relations have been sought between $m$ and pulse period, period derivative, fractional pulse width, dispersion measure, distance, timing-age, radio luminosity, and surface field strength, as tabulated by Manchester and Taylor (1981). The method used in

**Table 2. $\chi^2$ for temporal variations in pulsars**

| Pulsar | Dispersion measure (cm$^{-3}$ pc) | Galactic coordinates $l_0$ | Galactic coordinates $b_0$ | No. of observations 160 MHz | No. of observations 80 MHz | Modulation index 160 MHz | Modulation index 80 MHz | Reduced $\chi^2$ $[\chi^2/(n-1)]$ 160 MHz | Reduced $\chi^2$ $[\chi^2/(n-1)]$ 80 MHz |
|---|---|---|---|---|---|---|---|---|---|
| 0450−18 | 39·9 | 217·1 | −34·1 | 4 | — | 0·15 | — | 1·24 | — |
| 0628−28 | 34·4 | 237·0 | −16·8 | — | 3 | — | 0·36 | — | 25·8 |
| 0740−28 | 73·8 | 243·8 | −2·4 | 3 | — | 0·28 | — | 16·2 | — |
| 0835−41 | 147·6 | 260·9 | −0·3 | 4 | — | 0·29 | — | 3·17 | — |
| 0919+06 | 27·3 | 225·4 | +36·4 | 4 | 4 | 0·38 | 0·55 | 7·01 | 23·2 |
| 0943+10 | 15·4 | 225·4 | +43·1 | — | 4 | — | 0·56 | | 75·9 |
| 0950+08 | 3·0 | 228·9 | +43·7 | 3 | 3 | 0·66 | 0·31 | 486 | 29·3 |
| 1114−41 | 41·4 | 284·5 | +18·1 | 3 | — | 0·16 | — | 1·23 | — |
| 1133+16 | 4·8 | 241·9 | +69·2 | 5 | 4 | 0·62 | 0·90 | 56·5 | 330 |
| 1237+25 | 9·3 | 252·5 | +86·5 | 4 | 3 | 0·56 | 0·35 | 25·8 | 2·86 |
| 1541+09 | 35·0 | 17·8 | +45·8 | 5 | 4 | 0·27 | 0·33 | 13·9 | 11·4 |
| 1604−00 | 10·7 | 10·7 | +35·5 | 4 | 3 | 0·40 | 0·57 | 33·1 | 75·6 |
| 1642−03 | 35·7 | 14·1 | +26·1 | 4 | 4 | 0·12 | 0·49 | 1·76 | 24·4 |
| 1706−16 | 24·9 | 5·8 | +13·7 | 4 | 5 | 0·44 | 0·44 | 10·7 | 15·2 |
| 1749−28 | 50·9 | 1·5 | −1·0 | 3 | 4 | 0·43 | 0·30 | 72·6 | 9·62 |
| 1818−04 | 84·4 | 25·5 | +4·7 | 4 | — | 0·36 | — | 11·9 | — |
| 1907+10 | 144·0 | 44·8 | +1·0 | 3 | — | 0·22 | — | 3·86 | — |
| 1911−04 | 89·4 | 31·3 | −7·1 | 4 | — | 0·21 | — | 2·57 | — |
| 1915+13 | 94·0 | 48·3 | +0·6 | 3 | — | 0·32 | — | 10·0 | — |
| 1919+21 | 12·4 | 55·8 | +3·5 | 4 | — | 0·60 | — | 135 | — |
| 1933+16 | 158·5 | 52·4 | −2·1 | 3 | — | 0·09 | — | 0·81 | — |
| 2016+28 | 14·2 | 68·1 | −4·0 | 4 | — | 0·69 | — | 47·6 | — |
| 2020+28 | 24·6 | 68·9 | −4·7 | 5 | — | 0·38 | — | 18·8 | — |
| 2045−16 | 11·5 | 30·5 | −33·1 | 4 | 3 | 0·21 | 0·42 | 2·24 | 17·9 |

the present investigation was to make scatter plots and fit linear power-law and exponential regression equations.

We found a highly significant relationship between modulation index and dispersion measure. A less significant but probably real connection appeared to be present between modulation index and period derivative.

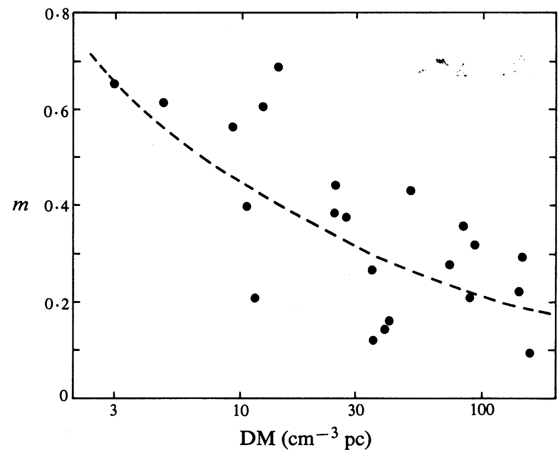


**Fig. 3.** Scatter plot of modulation index $m$ against dispersion measure (DM) for flux variations in 22 pulsars. The dashed curve is the fitted power-law regression equation $m = 0 \cdot 92(\mathrm{DM})^{-0 \cdot 32}$, where DM has units $cm^{-3}$ pc.

Fig. 3 shows a scatter plot of $m$ against dispersion measure (DM). The power-law regression equation plotted in Fig. 3, $m = 0 \cdot 92(\mathrm{DM})^{-0 \cdot 32}$ with a standard error in the index of $\pm 0 \cdot 12$, is significant at the 99·7% confidence level. A similarly significant power-law regression equation with an index of $-0 \cdot 36 \pm 0 \cdot 09$ is obtained for $m$/distance; this, however, is to be expected, because pulse distances are estimated from their dispersion measures with the help of a model for the electron density distribution in the Galaxy.

The weaker dependence of modulation index on period derivative $\dot{P}$ is illustrated in Fig. 4, which shows the distributions of $m$ when pulsars with low and high values of $\dot{P}$ are considered separately. A Kruskal–Wallis ranking test indicates that the distributions differ at the 95% confidence level. The tentative conclusion from Fig. 4 is that pulsars with lower period derivatives tend to show more intrinsic flux variability.

The correlation between the flux variations at widely separated frequencies is important in establishing the mechanisms that generate them; this is true whether the variations are intrinsic to the pulsar or are imposed by slow interstellar scintillation. We do not have enough simultaneous measurements of the 80 and 160 MHz fluxes to find correlations for individual pulsars, but we have established a *lower limit* to the *average* correlation coefficient between the flux variations for seven pulsars by the following method. We selected seven pulsars which each had $\geqslant 4$ simultaneous measurements of 80 and 160 MHz pulsed flux and found the median flux at each frequency for each of the pulsars (using any additional non-simultaneous flux measurements if available).

In order to minimize the effect of the differences in median flux on computing a correlation coefficient, the individual flux values were normalized to a common flux density by using the ratio of median to normalizing flux. We thus approximately reproduced an 'average pulsar' with 36 pairs of measured pulsed flux. The linear regression of the 80 MHz set on the 160 MHz set yielded a correlation coefficient of $r = 0 \cdot 55$, which is significant at the $99 \cdot 9\%$ confidence level. The degree of correlation obtained by this method underestimates the correlation that would have been obtained between 36 simultaneous measurements on one pulsar, due to the fact that the median pulsed fluxes used in the normalizing process would differ randomly and significantly from the median that would have been obtained in a much larger set of measurements on a single pulsar. The significance of the observed correlation will be discussed in Section 5.

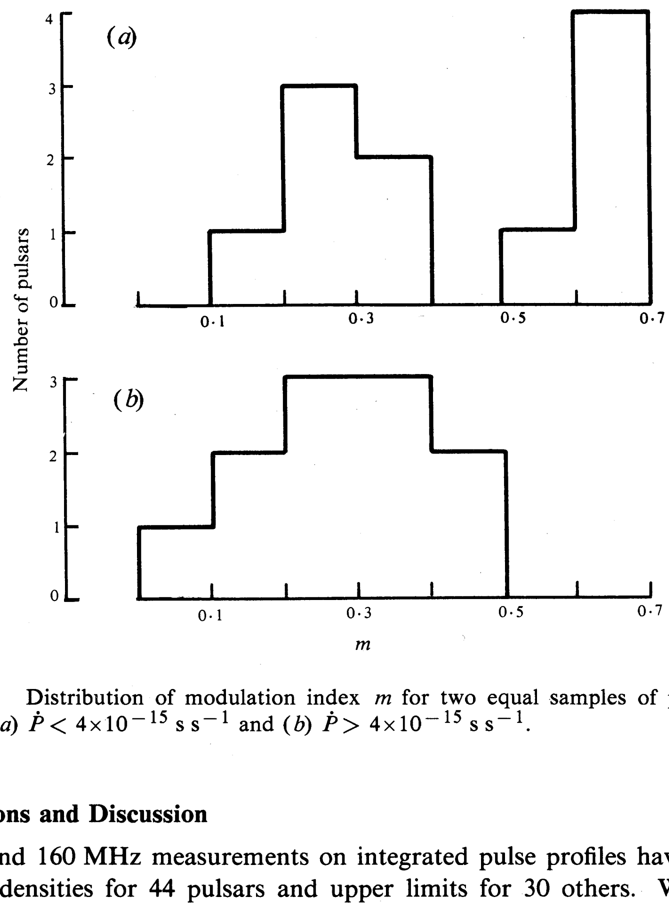


**Fig. 4.** Distribution of modulation index $m$ for two equal samples of pulsars with (*a*) $\dot{P} < 4 \times 10^{-15}$ s s$^{-1}$ and (*b*) $\dot{P} > 4 \times 10^{-15}$ s s$^{-1}$.

## 5. Conclusions and Discussion

Our 80 and 160 MHz measurements on integrated pulse profiles have resulted in pulsed flux densities for 44 pulsars and upper limits for 30 others. We found the following general characteristics present in the data:

(i) a progressive flattening of the radio spectra from high to low frequencies,

(ii) no relation between metre-wave spectral index and other measured pulsar parameters,

(iii) most pulsars show significant flux variations on a month-to-month time scale,

(iv) flux variations are well correlated at 80 and 160 MHz,

(v) flux variability is inversely correlated with the extrinsic property of dispersion measure and possibly with the intrinsic period derivative.

The form of the radio spectrum is closely connected with the generating mechanism and perhaps with the transmission properties of the pulsar magnetosphere. There seems little possibility that the progressive flattening of the spectrum could be due to free–free absorption in the ionized interstellar medium; if such were the case one would expect a definite turnover and a steep decrease in flux at the lowest frequencies. Of the numerous models that have been constructed very few give quantitative predictions for the spectrum of the pulsed flux. An important exception is the model first proposed by Radhakrishnan and Cooke (1969) involving coherent curvature radiation from charges traversing open field lines near the magnetic poles. This model was further developed by Tademaru (1971), who found that for a thin sheet of radiating charges (thickness $d < \lambda$) the spectral index varies from $-0\cdot5$ at low frequencies to $-2$ at high frequencies. It is evident that our results shown in Fig. 2 support this model, although it is not clear whether other quite different models might not also predict similar spectra if developed further.

The fact that there is no discernible relation between metre-wave spectral index and the measurable properties of period, period derivative and fractional pulse width indicates, we believe, that the generating mechanism and source location in the pulsar magnetosphere are not sensitive to or do not influence these parameters. The lack of a measurable effect due to the period is particularly interesting, as (i) the rotation rate determines the corotating volume about the neutron star and thus influences the magnetic field strength and relativistic beaming factors for sources in the 'closed-field' theories and (ii) in the 'open-field' polar models (e.g. Goldreich and Julian 1969) the electric potential difference across the polar cap that is available for accelerating electric charges depends upon the square of the angular velocity.

The significant relation between flux variability and dispersion measure is probably due to slow scintillation in the interstellar medium. The basic relation is probably with pulsar distance rather than with total columnar electron content. This conclusion is prompted by the evidence from the well-studied short-period scintillations and pulse broadening that the deviations in electron density responsible for interstellar scattering represent only a minor modulation (say $\sim 0\cdot1\%$) of the average electron density.

The strong modulation of the pulsed flux and its weak inverse dependence on pulsar distance found in the present data are not completely in agreement with the slow interstellar scintillation model proposed by Goodman and Narayan (1985). These authors found that a Kolmogorov spectrum ($\beta = 11/3$) of interstellar turbulence produces weak refractive intensity changes as opposed to our high modulation indices, but they did predict the weak inverse dependence on pulsar distance that we appear to observe. They obtained strong intensity changes when $\beta > 4$, but in this case their equations predict no dependence on distance.

The tentative rather weak inverse dependence of modulation index on the period derivative is difficult to interpret in terms of the physical parameters of the pulsar magnetosphere that could influence the intensity of the radio emission. Any of the quantities that are known to be related to the period derivative, such as age, magnetic field and braking torque, may somehow influence the stability of the emission.

However, in the absence of a theoretical model for the pulsar emission that includes a consideration of the stability of conditions in the emitting region, it is not possible to make further progress at present. If the relation is confirmed by more extensive observation then the effect may be important in deciding between different models for the pulsar emission.

In conclusion, it is clear that the present investigation has brought to our attention some possible fundamental relations between measurable pulsar characteristics and the parameters of the interstellar medium and of the pulsar that can be derived from them. The results of these rather limited observations should be confirmed and extended by a more comprehensive observing program investigating some of these findings in much more detail. Unfortunately the CCA is no longer operational; however, some existing single-frequency filled arrays are capable of making extended measurements of the flux variations in a useful number (say 30 or 40) of pulsars with a view to separating the slow interstellar scintillations from the intrinsic slow variability. This should lead to more detailed information on the scale and location of large refractive structure in the interstellar medium as well as defining more conclusively the generating mechanism and its location in the pulsar magnetosphere.

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