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# Energy Spectra and Pulse Shapes of Pulsars at Metre Wavelengths

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*Abstract*

Flux densities, pulse energy densities and mean pulse shapes of pulsars have been measured at frequencies of 61 and 102·5 MHz. In general, with increasing wavelength, the mean pulse width becomes larger and its profile becomes less complex. Instantaneous spectra obtained by simultaneous measurements show marked variability, but the mean spectrum is a stable characteristic of each pulsar. A common feature of pulsar mean spectra is a low frequency cutoff below about 100 MHz. The nature of this cutoff is discussed.

## 1. Introduction

In order to obtain the general characteristics of pulsar radio emission and their relationships with the age, period and luminosity of the pulsar, one needs uniform comparable data on flux densities, spectra, pulse energy densities and pulse shapes. Extensive data are available at 408 MHz and higher frequencies, but very few measurements have been made at lower frequencies. Accordingly, we have begun a survey of known pulsars at a frequency of 102·5 MHz in which we measure flux density, pulse energy density and pulse shape.

This program is being carried out under the U.S.S.R.–Australia agreement on scientific and technological cooperation. The U.S.S.R. part of the program covers pulsars of the northern hemisphere, and is performed in Puschino using the BSA radiotelescope of the Radio Astronomical Observatory, Lebedev Physical Institute. The Australian part of the program covers pulsars of the southern hemisphere, and this will be performed in Hobart using the radiotelescope of the University of Tasmania. The near equatorial pulsars will be observed by both groups to check the uniformity of the data.

The present paper reports data from the first part of the pulsar survey at 102·5 MHz, as well as some other results from an investigation of pulsar radio emission at metre wavelengths also carried out by the Radio Astronomical Observatory of the Lebedev Physical Institute. Part of the observations were performed in joint programs with the Jodrell Bank Radio Astronomical Observatory (U.K.) and the Institute of Radiotechnique and Electronics, Academy of Sciences of the Ukraine.

The pulsar survey at 102·5 MHz was performed using the new large radiotelescope BSA (Vitkevich *et al.* 1976) at Puschino, 100 km south of Moscow. The antenna of this radiotelescope is a large phased array, $72\times10^3$ m$^2$ in area ($384\times187$ m), containing 16384 dipoles. A matrix scheme forms multiple antenna patterns allowing simultaneous observations with 16 beams. The antenna is linearly polarized, and the frequency bandwidth is 3 MHz near a central frequency of 102·5 MHz.

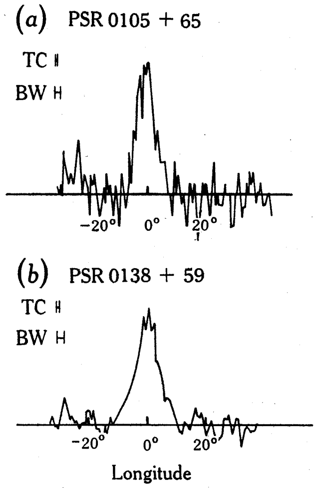


**Fig. 1.** Examples of observational records for (*a*) PSR 0105+65 and (*b*) 0138+59 at 102·5 MHz. The widths TC and BW represent the broadening of the pulse due to the receiver time constant and bandwidth respectively. The integration time is about 7 min.

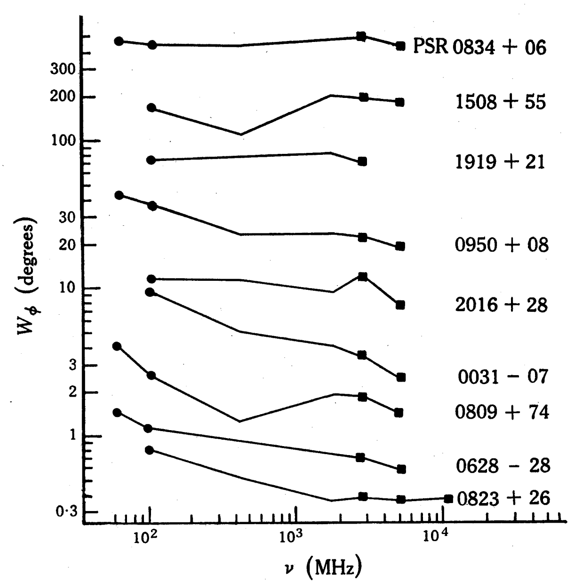


**Fig. 2.** Width $W_\phi$ at half power of a mean pulse for the indicated pulsars shown as a function of frequency $\nu$. The vertical axis has an arbitrary zero.

In order to obtain additional data on the frequency dependence of flux densities, pulse energy densities and pulse shapes, we also made observations at 61 MHz. These observations were performed using the east–west arm of the Lebedev Physical Institute cross-type radiotelescope. This is a parabolic cylinder reflector measuring 1 km × 40 m and is operated in the 30–120 MHz frequency band. Examples of typical observations (PSR 0105+65 and 0138+59) are presented in Fig. 1.

**Table 1. Pulsar radio emission data**

For description of entries, see Section 2 of text

| (1) PSR No. | (2) $\nu$ (MHz) | (3) $\varepsilon$ (mJy s) | (4) $S$ (Jy) | (5) No. of obsns | (6) $W_t$ (ms) | (7) $W_\phi$ (°) | (8) $\Delta t$ (ms) | (9) $\Delta\phi$ (°) |
|---|---|---|---|---|---|---|---|---|
| 0031−07 | 61 | 930±530 | 1·0±0·6 | 3 | | | | |
| | 102·5* | 450±110 | 0·48±0·11 | 4 | 92 | 35 | | |
| 0105+65 | 102·5 | 37±10 | 0·03±0·01 | 6 | 22 | 6 | | |
| 0138+59 | 102·5 | 75±25 | 0·06±0·02 | 8 | 17·5 | 5·1 | | |
| 0301+19 | 102·5 | 75±10 | 0·05±0·01 | 5 | | | | |
| 0329+54 | 61 | | | | 9 | 4·5 | | |
| | 83 | 750±140 | 1·05±0·2 | 4 | | | | |
| | 102·5* | 450±60 | 0·6±0·1 | 19 | 6·9 | 3·4 | 25 | 12·6 |
| 0355+54 | 102·5 | 8±3 | 0·05±0·02 | 4 | | | | |
| 0450−18 | 102·5 | 190±60 | 0·35±0·1 | 4 | | | | |
| 0525+21 | 102·5 | 550±40 | 0·15±0·01 | 4 | 260 | 24 | 200 | 19·2 |
| 0540+23 | 102·5 | 13±4 | 0·05±0·02 | 2 | | | | |
| 0628−28 | 61 | 2340±360 | 1·9±0·03 | 7 | 105 | 30 | | |
| | 102·5 | | | | 84 | 24 | | |
| | 110 | 960±140 | 0·8±0·1 | 8 | | | | |
| 0809+74 | 61 | 2980±530 | 2·3±0·4 | 8 | 125 | 35 | | |
| | 102·5 | 2390±570 | 1·85±0·44 | 12 | 78·8 | 22 | | |
| 0823+26 | 61 | 545±80 | 1·0±0·2 | 6 | | | | |
| | 102·5* | 390±90 | 0·7±0·2 | 9 | 8·4 | 5·5 | | |
| 0834+06 | 61 | 3970±540 | 3·1±0·4 | 10 | 24 | 6·8 | | |
| | 102·5* | 2400±330 | 1·9±0·3 | 15 | 22·6 | 6·4 | | |
| 0943+10 | 61 | | | | 70 | 23 | | |
| | 102·5 | | | | 50 | 20 | | |
| 0950+08 | 61 | 220±100 | 0·9±0·4 | 9 | 16·2 | 23 | | |
| | 102·5 | | | | 14·2 | 20·2 | | |
| 1112+50 | 102·5 | ≤80 | ≤0·05 | 4 | | | | |
| 1133+16 | 61 | 890±180 | 0·75±0·15 | 11 | 47 | 14·2 | 37·0 | 11·2 |
| | 102·5 | 850±180 | 0·7±0·15 | 13 | 39 | 11·8 | 31 | 9·4 |
| 1237+25 | 61 | ≤420 | ≤0·3 | 6 | | | | |
| | 83 | 600±120 | 0·4±0·1 | 4 | | | | |
| | 102·5 | 630±60 | 0·46±0·04 | 19 | 72 | 18·4 | 60 | 15·6 |
| 1508+55 | 61 | 1000±350 | 1·35±0·47 | 4 | | | | |
| | 102·5 | 1020±120 | 1·4±0·2 | 11 | 13·5 | 6·6 | | |
| 1541+09 | 61 | <480 | <0·6 | 4 | | | | |
| | 102·5 | 340±40 | 0·45±0·05 | 9 | 37 | 18 | | |
| 1604−00 | 102·5 | 250±60 | 0·6±0·2 | 5 | | | | |
| 1642−03 | 61 | <290 | <0·8 | 4 | | | | |
| | 102·5 | 290±130 | 0·75±0·35 | 8 | 10·7 | 9·9 | | |
| 1706−16 | 102·5 | 80 | 0·1 | 6 | | | | |
| 1822−09 | 102·5 | 690±150 | 0·9±0·2 | 2 | 11·5 | 5·4 | | |
| 1831−04 | 102·5 | 340±150 | 1·2±0·5 | 3 | | | | |
| 1919+21 | 61 | 3800±590 | 2·8±0·4 | 12 | | | | |
| | 102·5 | 1520±230 | 1·1±0·2 | 12 | 28 | 7·5 | | |
| 1929+10 | 102·5 | ~60 | ~0·25 | 1 | 8·4 | 13·3 | | |
| 2016+28 | 102·5 | 120±15 | 0·2±0·02 | 10 | 11 | 7 | | |
| 2020+28 | 102·5 | 40±6 | 0·12±0·02 | 3 | 19 | 20 | 15 | 15·7 |
| 2154+40 | 102·5 | ~300 | ~0·2 | 1 | 60 | 14 | | |
| 2217+47 | 61 | 1790±750 | 3·3±1·4 | 4 | 18 | 6·3 | | |
| | 102·5 | 350±60 | 0·6±0·1 | 5 | 7·2 | 4·8 | | |
| 2223+65 | 102·5 | 70±13 | 0·1±0·02 | 11 | 20 | 10·5 | | |
| 2303+30 | 102·5 | 90±28 | 0·06±0·02 | 8 | 26 | 6 | | |

* The systematic error at 102·5 MHz is about 30%; this error is not included in the table.

## 2. Catalogue

A list of observed pulsars is presented in Table 1, where they are given in order of PSR number (column 1). Columns 2, 3, 4 and 5 list the observing frequency $\nu$, the corresponding mean values obtained for the pulse energy density $\varepsilon$ and the flux density $S$, and the number of observations used in deriving these values. Data at 61 MHz were obtained for 13 pulsars, at 102·5 MHz for 30 pulsars, at 83 MHz for 2 pulsars and at 110 MHz for 1 pulsar.

In addition to energy and flux density measurements, the mean pulse shapes were also measured. Columns 6 and 7 list the mean half-power pulse widths $W_t$ and $W_\phi$ in time and angle respectively. Data at 61 MHz were obtained for 8 pulsars and at 102·5 MHz for 25 pulsars. For five two-component pulsars, the mean intervals $\Delta t$ and $\Delta\phi$ between the components in time and angle respectively were also measured. These are given in columns 8 and 9.

## 3. Pulse Shapes

We have compared the pulse shapes and pulse widths from our measurements (columns 6 and 7 of Table 1) with published data for 408 MHz and higher frequencies (Lyne *et al.* 1971; Manchester 1971; Sieber *et al.* 1975). This comparison leads to the following three conclusions:

(i) There is a tendency for the width of the mean pulse shape to increase with wavelength. For different pulsars the pulse width either broadens (especially in the 61–408 MHz frequency interval) or remains constant within the measurement errors. This conclusion is illustrated in Fig. 2, where the half-power widths of mean pulses for different pulsars are plotted as a function of frequency. The broadening of the pulses is observed for pulsars of the 'simple', 'complex' and 'drifting' pulsar types. Figs 3*a* and 3*b* show mean pulse shapes for a drifting-type pulsar PSR 0809+74 and a simple-type pulsar PSR 0823+26, over a wide range of frequencies. It is necessary to point out that interstellar scattering for the pulsars observed by us is not a significant effect.

(ii) With increasing wavelength the pulse shape generally becomes less complex. No new components were observed in the pulse shapes at 61 or 102·5 MHz when compared with the shapes at high frequencies, and in some cases a disappearance or smoothing of components was observed. Figs 3*c* and 3*d* show examples of simplification in the pulse shape with increasing wavelength for PSR 0834+06 and 1508+55. We suggest that this simplification is due to a difference in spectra for different parts of the pulse.

(iii) Five of the pulsars observed by us (PSR 0329+54, 0525+21, 1133+16, 1237+25 and 2020+28) have a well-defined two-component structure at 102·5 MHz. The pulse shapes of these pulsars remain similar at 61 MHz, but the angular interval $\Delta\phi$ between components increases with wavelength.

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**Fig. 3** (*opposite*). Mean pulse shapes as a function of longitude of (*a*) a drifting-type pulsar PSR 0809+74, (*b*) a simple-type pulsar PSR 0823+26, (*c*) and (*d*) pulsars PSR 0834+06 and 1508+55 which illustrate the simplification in pulse shape with increasing wavelength, and (*e*) and (*f*) the double-component pulsars PSR 2020+28 and 0525+21. The observation frequencies (in the 61–4900 MHz range) are indicated.

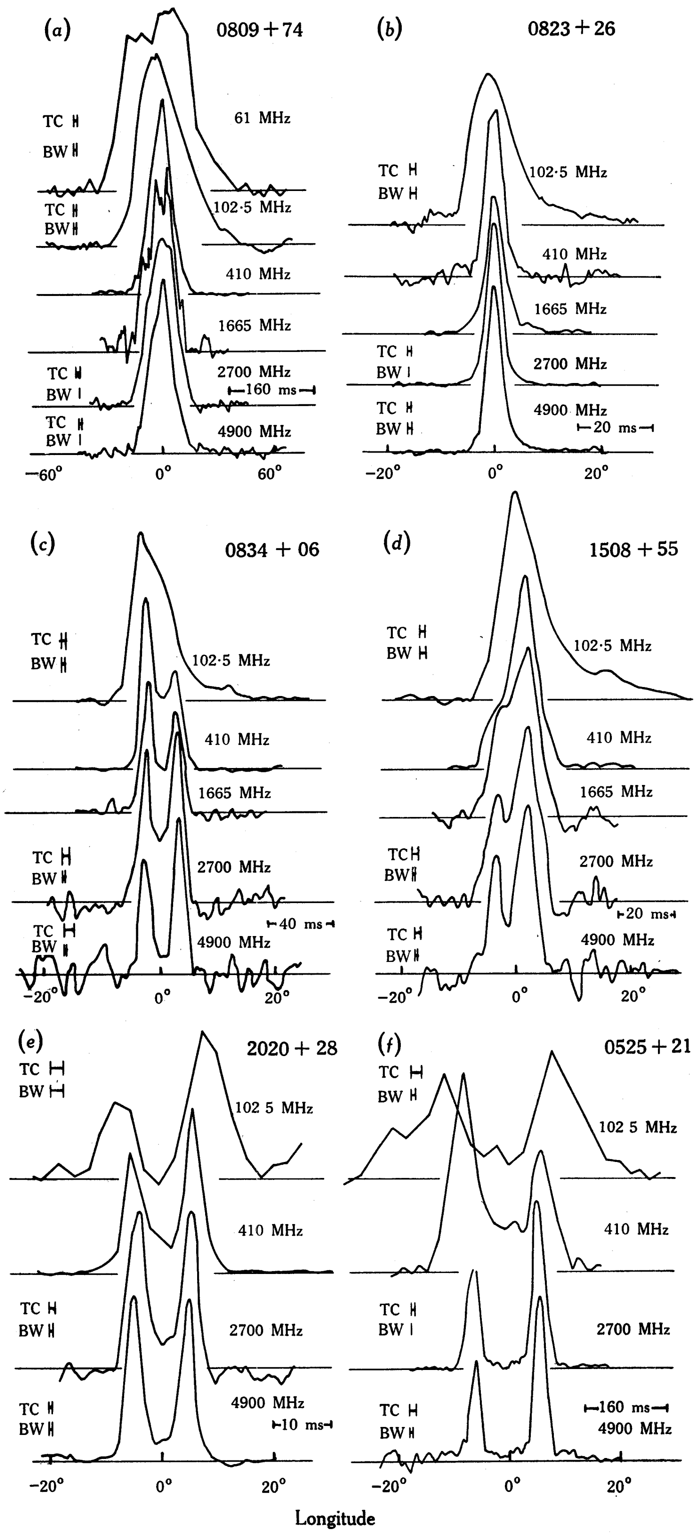
(a)
0809+74
TC
BW
61 MHz
102·5 MHz
410 MHz
1665 MHz
2700 MHz
160 ms
4900 MHz
−60°
0°
60°
(b)
0823+26
102·5 MHz
410 MHz
1665 MHz
2700 MHz
4900 MHz
20 ms
−20°
0°
20°
(c)
0834 + 06
102·5 MHz
410 MHz
1665 MHz
2700 MHz
40 ms
4900 MHz
−20°
0°
20°
(d)
1508 + 55
102·5 MHz
410 MHz
1665 MHz
2700 MHz
20 ms
4900 MHz
−20°
0°
20°
(e)
2020 + 28
102 5 MHz
410 MHz
2700 MHz
4900 MHz
10 ms
−20°
0°
20°
(f)
0525 + 21
102 5 MHz
410 MHz
2700 MHz
160 ms
4900 MHz
−20°
0°
20°
Longitude

**Fig. 3**

Figs 3e and 3f give examples of such behaviour for PSR 2020+28 and 0525+21. It is interesting that the character of the frequency dependence of $\Delta\phi$ is approximately the same for all five pulsars (Fig. 4). For PSR 0525+21, 1133+16 and 1237+25 our measurements agree with previous data (Manchester and Taylor 1977). For PSR 2020+28 and 0329+54 (components III and IV) our data are new. One can represent this frequency dependence by the power law

$$\Delta\phi \propto \nu^{\beta},$$

where $\beta \approx -0{\cdot}25$ for $\nu \lesssim 1$ GHz and $\beta \approx 0$ for $\nu \gtrsim 1$ GHz. Values of $\beta$ for these five pulsars, obtained from our observations at 102·5 MHz and from the 408 MHz data, are all approximately $-0{\cdot}25$.* The individual $\beta$ values are: 0329+54 (components III and IV), $-0{\cdot}16$; 0525+21, $-0{\cdot}21$; 1133+16, $-0{\cdot}26$; 1237+25, $-0{\cdot}18$; 2020+28, $-0{\cdot}25$.

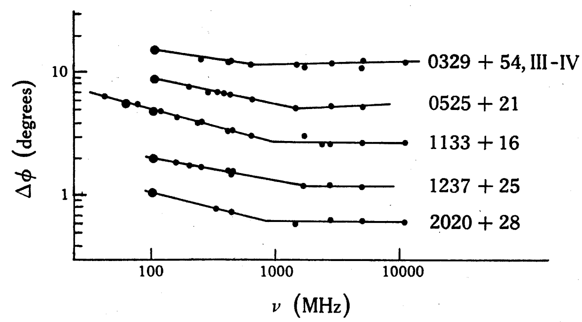


**Fig. 4.** Angular interval $\Delta\phi$ between subpulses in the indicated two-component pulsars as a function of frequency $\nu$. The vertical axis has an arbitrary zero.

We suggest a simple geometric explanation of the increasing interval $\Delta\phi$ with wavelength. A two-component pulse shape may be interpreted in terms of a hollow cone model. Since the angle of the cone formed by the magnetic flux lines will increase with distance from the surface of the neutron star, the increase of $\Delta\phi$ with $\lambda$ may be interpreted as the result of long wavelength radio emission being at greater distances from the surface of a neutron star. In the following section, we show that this suggestion also allows us to explain the form of the low frequency spectra of pulsars.

## 4. Spectra

The spectra of pulsars characterizes the radio emission mechanism, and so this is one of the important characteristics of pulsars, but the measurement of pulsar spectra is complicated by significant time variations in the intensity of the radio pulse emission. To obtain true spectra one needs simultaneous measurements over the whole spectral interval. Simultaneous measurements of spectra of nine pulsars (PSR 0329+54, 0628−28, 0809+74, 0950+08, 1133+16, 1237+25, 1508+55, 1642−03 and 1919+21) were obtained over a 60–1400 MHz frequency interval by

* Note that PSR 1913+16 reported by Cordes (1979) also has $\beta = -0{\cdot}25$.

Kuzmin *et al.* (1978), working under the U.S.S.R.–U.K. agreement on scientific and technological cooperation. The U.S.S.R. measurements were performed at the Puschino Radio Astronomical Observatory of the Lebedev Physical Institute, at 61 and 102·5 MHz. The U.K. measurements were performed at the same time using the Mark 1 radiotelescope of the Jodrell Bank Radio Astronomical Observatory, at 408 and 1420 MHz.

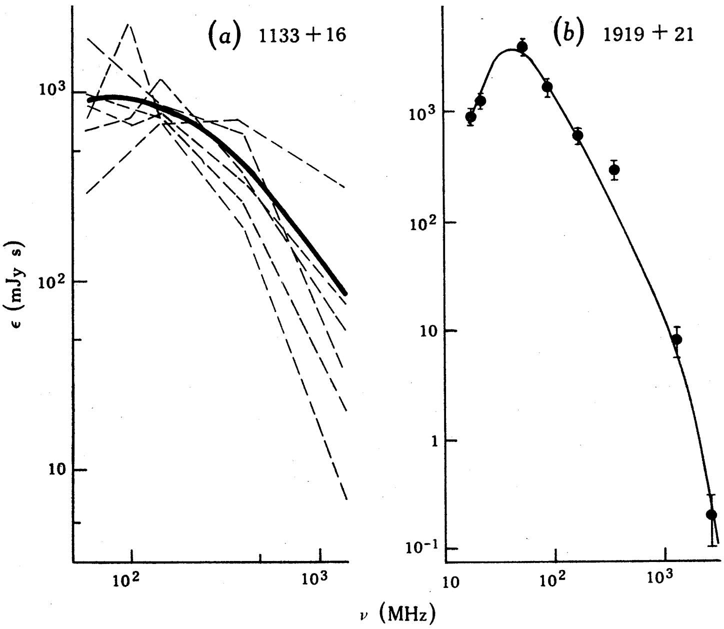


**Fig. 5.** Plots of (*a*) instantaneous spectra (dashed curves) for different days and the mean (full curve) spectrum of PSR 1133+16 and (*b*) the mean of PSR 1919+21.

The Puschino radiotelescope is a meridian transit instrument and observations could be made for only a few minutes each day. Fig. 5*a* shows the instantaneous spectrum of PSR 1133+16 on different days. There are significant day-to-day variations, not only in the intensity of the pulsar's radio emission but also in its spectrum. In the frequency interval 61–102·5 MHz, the variations of spectral index $\alpha$ were as high as $\Delta\alpha \approx 3$. There were even changes in the sign of $\alpha$. However, the mean spectrum, obtained by averaging for a long time, appears to be a stable and repeatable characteristic that is specific for each pulsar.

A characteristic feature of pulsar mean spectra is their decreasing steepness at lower frequencies, followed by low frequency cutoff. Such an effect was known previously, but only for a small proportion of pulsars. In our first measurements in collaboration with Jodrell Bank, we found a low frequency cutoff in the spectra of five of the nine pulsars under observation. Taking into account the stability of the mean spectra, we performed joint measurements with Yu. M. Bruck and B. Yu. Ustimenko (Bruck *et al.* 1978), using the UTR-2 radiotelescope of the Institute of Radiotechnique and Electronics, Academy of Sciences of the Ukraine. This enabled us to extend the spectra to lower frequencies, thus allowing us to detect a low frequency cutoff for three additional pulsars. The mean spectrum of PSR 1919+21 showing its low frequency cutoff is given in Fig. 5*b*. Only one pulsar (PSR 0628−28) out of the nine which we investigated showed no low frequency cutoff, which suggests that this feature may be characteristic of pulsar radio emission in general. For a sample of eight pulsars, the frequencies $\nu_{max}$ at which the mean pulsar spectrum attained its maximum were: 0329+54, 250 MHz; 0809+74, 70±20 MHz; 0834+06, 70±20 MHz; 0950+08, 115±40 MHz; 1133+16, 100±40 MHz; 1237+25, 150±50 MHz; 1642−03, 175±25 MHz; 1919+21, 60±20 MHz.

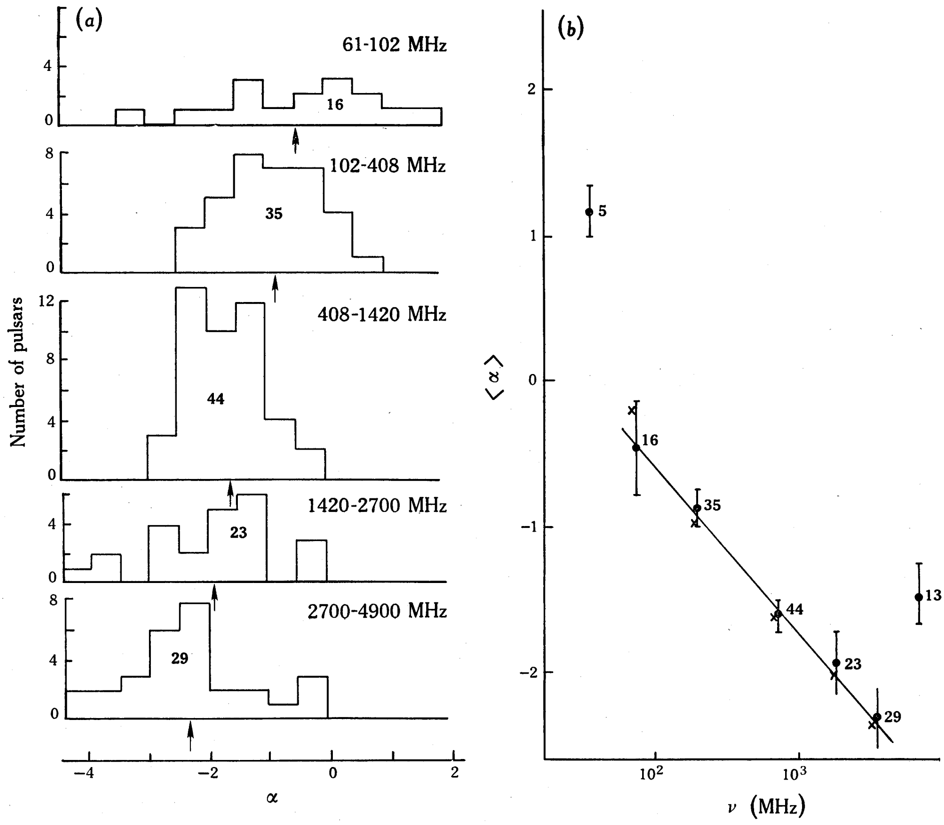


**Fig. 6.** Variation of spectral index α with frequency ν, showing (*a*) histograms of α for pulsars at the indicated frequencies (between 61 and 4900 MHz), with the mean ⟨α⟩ indicated by an arrow, and (*b*) the variation of ⟨α⟩ as a function of frequency ν. The number of pulsars included in each sample is indicated. The crosses in (*b*) represent values for a selected group of 14 pulsars with data common to each frequency interval.

One needs to emphasize that these low frequency cutoffs are for pulsars which differ significantly in their other parameters. There are short periods ($P = 0{\cdot}253$ s for 0950+08) and long periods ($P = 1{\cdot}337$ s for 1919+21), there are differences in ages of up to two orders of magnitude (0809+74 and 0834+06) and differences in luminosity of up to three orders of magnitude (0329+54 and 1133+16). Amongst this sample of eight there are pulsars of simple type (1642−03), drifting type (0809+74 and 1919+21) and complex type (1133+16 and 1237+25). These circumstances suggest that a low frequency cutoff in the mean spectrum is a characteristic feature for pulsars of all types.

In order to generalize the above suggestion we have analysed spectra for a larger number of pulsars. In Fig. 6*a* we plot histograms of spectral indices in different frequency intervals. Although there is a large scatter in these results, the mean spectral index changes systematically with frequency. This is shown in Fig. 6*b* where the mean spectral index $\langle\alpha\rangle$ is plotted as a function of frequency $\nu$ over the 61–4900 MHz frequency interval. This dependence may be represented by the empirical relation

$$\langle\alpha\rangle = 1\cdot 8 - 1\cdot 2\log_{10}\nu\,, \tag{1}$$

with $\nu$ in megahertz.

It should be noted that some of the data included in Fig. 6*a* refer to different pulsars in different frequency intervals, which could lead to a selection effect. We have guarded against this, however, by also calculating mean spectral indices for the 14 pulsars for which data are available over the whole 61–4900 MHz frequency interval. These values are shown in Fig. 6*b* by crosses; they do not essentially change the dependence. This dependence (equation 1) confirms the flattening of the spectra at low frequencies (together with the eventual cutoff) which was found from direct measurements.

The cause of the low frequency cutoff in pulsar spectra is not absolutely clear. It is not an interstellar scattering effect; experimental data on the decorrelation frequency bandwidth show that the effect of interstellar broadening is negligible even at decametric wavelengths (Rickett 1970; Shitov 1972). This is evident also from the fact that nearby pulsars (PSR 0950+08 and 1133+16) have a low frequency cutoff approximately at 100 MHz, but the more distant pulsar PSR 0628−28 does not show such a cutoff even at 61 MHz.

We emphasize also that a low frequency spectral cutoff is not an effect of free–free absorption in the intervening plasma, whether near the source or in the interstellar medium. If this were the case, the shape of the cutoff should follow an $\exp(-b\lambda^2)$ law and should be the same for all pulsars. However, the observed low frequency spectra have both sharp and slow cutoffs.

One possible interpretation was proposed by Malov (1978). He suggested that the exponent coefficient $b$ is not constant but is a function of frequency $b(\nu)$ which depends on the level in the pulsar's magnetosphere at which the frequency $\nu$ is emitted. If lower frequencies are emitted at larger distances from the surface of a neutron star, the low frequency cutoff of the spectrum will be slower than exponential. This is consistent also with our interpretation of the observed two-component separation as a function of wavelength, as discussed above. Other interpretations of the low frequency cutoff may also be suggested, e.g. a decrease in coherence. However, we believe that the cutoff, and the variation of spectral index with frequency, originate in the region of radio emission and are due to the pulsar radio mechanism itself rather than to a propagation effect.

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