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Pulsar Radio Spectra

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Abstract. A review of simultaneous and compiled spectra is presented, and a catalog of radio spectra for 340 pulsars reported. Pulsars with flux density measurements at three and more frequencies are included. Statistics of spectral indices and frequencies of the energy maximum and the break are presented, as well as the correlations with other pulsar parameters. The classification of 127 rich pulsar spectra has been made. Three main types of spectra are identified.

1. Simultaneous and compilation spectra

From the begining of pulsar observations, it was clear that flux densities of these objects show strong variations at all frequencies from 60 to 5000 MHz on timescales from milliseconds to days. To obtain spectra of pulsars radio emission it was necessary to make simultaneous measurements. The basic references for this type of observation and short comments are presented in Table 1. Simultaneous observations showed: 1) Pulsar spectra can be represented as power-law type $S \sim \nu^{-\alpha}$ with spectral index α close to 1.6. These spectra are much steeper than for other space objects; 2) a few spectra show a low-frequency turnover and a high-frequency break; 3) all spectra exhibit significant variations of their form, but the average spectrum of a few days' observations corresponds generally to that compiled from all non-simultaneous observations.

First compiled spectra for 27 pulsars have been presented by Sieber in 1973. He obtained mean spectral index $\bar{\alpha} = 1.62$, showed that 8 pulsars have the low-frequency turnower and pointed out that one must be careful to compare energy values at different frequencies, as the intrinsic intensity can be time dependent. We know now that the most part pulsar flux variations are caused by diffractive and refractive interstellar scintillations, but the question of intrinsic variations is still open. For example, we can see in the spectrum of PSR 1133+16 (Fig. 1a) the strong variations of energy in all frequency range including 10 GHz, where the influence of the scintillations must introduce variations of less than 10%. One of the problems is how to take into account the errors of the individual measurements to obtain the real pulsar spectra, because more than half of authors don't give any error bars and others don't estimate the influence of interstellar scintillations. In this case the better way to obtain a reliable spectrum is to use the mean values of energy, which have been measured at adjacent frequencies (Malofeev, Malov 1980; Malofeev et al. 1994). But if there is only one measurement of energy at every frequency the form of spectrum can be changed to a degree much larger than the error bars, when new measurements

Table 1. List of basic papers with pulsar spectra

PSR or num.	Freq. range (GHz)	Num. of freq.	Reference	Comments
0950+08, 1133+16	0.15-0.9	3	Lyne A.,Ricket B., 1968,Nature 218,326	$S \sim \nu^{-\alpha}$
1919+21	0.09-1.4	4	Robinson et al.,1968 Nature 19, 218, 1143	Maximum frequency
4	0.06-0.1	4	Alekseev et al.,1970 I.V.Radiofis.13,1810	Change of form
0531-21	0.07-0.6	4	Rankin et al.,1970 ApJ 162, 707	$S \sim \nu^{-\alpha}$, $\alpha = 2.9$
0950+08, 1133+16	1.4-5	2	Backer D.C.,1972 ApJ 174, L157	Break frequency
12	0.15-0.4	3	McLean A.I.O.,1973 MNRAS 165, 133	Max.freq. 3 PSR
10	0.25-8.1	6	Backer D.,Fisher F. 1974, ApJ 189, 137	$S \sim \nu^{-\alpha}$, $\alpha = 1.6 - 3.0$
9	0.06-1.4	5	Kuzmin et al.,1978 MNRAS 185, 441	4 telescopes, aver.spect.
2	0.02-1.4	7	Bruck et al.,1978 AZh 55, 1031	corresp. to compliled one
27	0.15-2.7	4-7	Siber W.,1973 A& A, 28, 237	8 PSR Max.freq. $S \sim \nu^{-\alpha}$,
1133+16	0.15-24	7	Bartel et al.,1978 A& A 68, 361	Spectra of components
39	0.02-15	2-17	Malofeev,Malov,1980 AZh 57,90	Average spectra $\nu_m(P), \nu_B(P)$
52	0.02-23	3-18	Izvekova et al., 1981 Ap&SS 78, 45	44 max. freq., luminosity
74	0.08-1.4	2-4	Slee et al., 1986 Aust.J.Phys.39,103	Southern PSR, spect.indices
~ 45	0.4-1.4		Lyne,Manchester,88 MNRAS 234,477	Depend.$\alpha(P)$ for comp.
4	0.4-3	5-23	Foster et al., 1991 Ap.J. 378, 687	Ms PSR, spec. index of comp.
45	0.02-24	5-17	Malofeev et al., 1994 A&A 285, 201	Two group of spectra
7	34.8	1-2	Wielebinski et al., 1993,A&A 272, L13	Very high frequency
1822-09	0.03-24	14	Gil et al.,1994 A&A 282, 45	Spectra of interpulse, comp.
8	28-35	1-4	Kramer et al.,1995 A&A (in press)	Turn up for 2 PSR
328	0.4-1.6	2-5	Lorimer et al.,1995 MNRAS (in press)	Depend $\alpha(P)$, $\alpha(T)$.
330	0.02-35	3-20	Malofeev V.,1996	Catalog

are added. It may be better to speak about more or less probable spectra, taking into account the number and duration of the observations.

In any case a few attempts have been made to find any correlations between pulsar spectra and other pulsar parameters. Malofeev and Malov (1980) have shown that there are correlations between frequency of maximum (ν_m), break frequency (ν_b) and period (P) as well as between these two frequencies ν_m and ν_b. A significant correlation between two spectral indices was found for pulsars with a break in their spectrum (Malofeev et al. 1994). Lorimer et al. 1995 have shown that there are connections of spectral index at range 0.4-1.6 GHz with period and age, but the scatter in the data is large. A very important investigation has been made to obtain the spectra of the mean profile components for PSR 1133+16 (Bartel et al. 1978) and two components and interpulse of PSR 1822-09 (Gil et al. 1994). Lyne and Manchester (1988) have obtained the corrēlations between relative spectral index for inner and outer components with the period.

New observations at 28-34 GHz were made at the Bonn radiotelescope, and for two objects an indication of a turn-up in the spectrum was found at frequencies above 30 GHz (Wielebinski et al. 1993; Kramer et al. 1995). But we must beware the possibility of intrinsic flux variations.

2. Catalogue of pulsar radio spectra

We have made measurements of 160 weak pulsars at 102 MHz at Pushchino observatory over a period of 1.5 year (Malofeev et al. in preparation). Seiradakis et al. (1995) have published the flux density measurements at 1.4, 4.7 and 10.6 GHz for 150, 70 and 40 pulsars respectively. Lorimer et al. (1995) have presented new observations covering three years for 328 pulsars at 2-5 frequencies in the range 0.4-1.6 GHz. We added all these and other new data to the collection of pulse energies which was begun by Sieber (1973) and continued by Malofeev and Malov (1980), Malofeev et al. (1994). The collection contains more than 120 references with measurements of pulsar energy.

Our catalog consists of the 340 pulsar radio spectra, with measurements of energy at three or more well separated frequencies ($\nu_h/\nu_l > 3$, where ν_h and ν_l are the highest and the lowest frequency). We tried to fit a single power law to all spectra, but there is a large group of pulsars which requires two (Malofeev et al. 1994) or three power laws (Gil et al. 1994). Most spectra (114 PSR) with low frequency observations ($\nu \leq 0.1$ GHz) show a turnover between 25 MHz and 800 MHz. The distributions of spectral indices for 284 objects (with simple power law dependence) and frequency of maximum for 114 pulsars are presented in Fig. 1b,c. The mean spectral index is $\bar{\alpha} = 1.71$, $\sigma = 0.57$. Important feature demonstrates the distribution of spectral indices for 10 millisecond pulsars. It is fairly broad without peaking distribution.

The examination of data for correlation between spectral index α, frequency of maximum ν_m and P, $\dot{P}$, surface magnetic field strength B, characteristic age $\tau = P/2\dot{P}$ and the integral luminosity L (Malov et al. 1994) has been made. Most of these plots have large scatter; we show the more interesting of them in Fig. 2. Three diagrams with spectral index show a tendency rather, but the formal fitting was made. The correlation between ν_m and P for 114 pulsars confirms one obtained for 17 pulsars by Malofeev and Malov (1980) first.

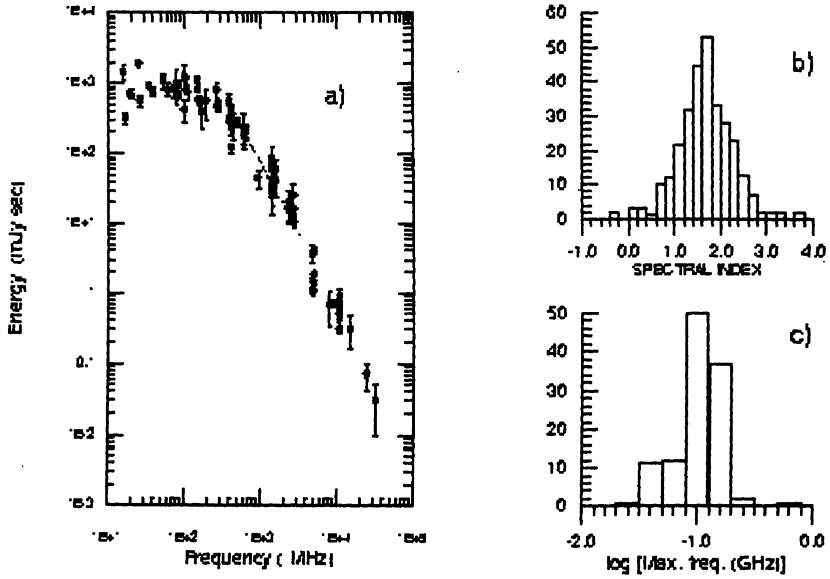


Figure 1. a) Spectrum of pulsar PSR 1133+16; b) Histogram showing the distributions of spectral indices for the 284 pulsars; c) The distributions of the maximum frequency for the 114 pulsars.

3. Classification of spectra

127 rich and over a wide frequency range ($\nu_h/\nu_l \geq 40$) spectra have been chosen for the classification. The spectra for 63% of pulsars can be modelled by a simple power law, while 35% pulsars apparently require two power laws. We suggest a classification of pulsar radio spectra: the first group to call class S (simple) and the second group class B (broken type of spectra). Most spectra show a low-frequency turnover and we suggest to call these spectra as S^m or B^m subclasses (Fig. 3). Pulsars which have a turn-up in spectra could be marked as S_t or B_t subclasses (PSR 2021+51 in Fig.3). The third class of spectra C (complex) includes only PSR 1822-09 at present. It can be represented by three power laws (Gil et al. 1994).

The distributions of spectral indices for 80 pulsars of class S and indices α_1 and α_2 for 46 pulsars of class B are shown in Fig.4. The α_2 distribution shows two or three components.

We examined the data for correlation between spectral parameters α, α_1, α_2, ν_m, ν_b and P, $\dot{P}$, B, T, L. The most significant of these are shown in Fig. 5. In the maximum frequency-break frequency diagram there are two possible dependencies. Three other diagrams show the decrease index α_2, the frequencies ν_b and ν_m with increases of the characteristic age. All these (Fig. 3,5) correlations and tendencies demonstrate the rough evolution of pulsar spectra. To under- stand the reason why all our diagrams show large amounts of scatter we must understand which parameters can influence the form of pulsar spectra. There are: P, $\dot{P}$, T, B, the angle between spin and magnetic axes (φ), the impact

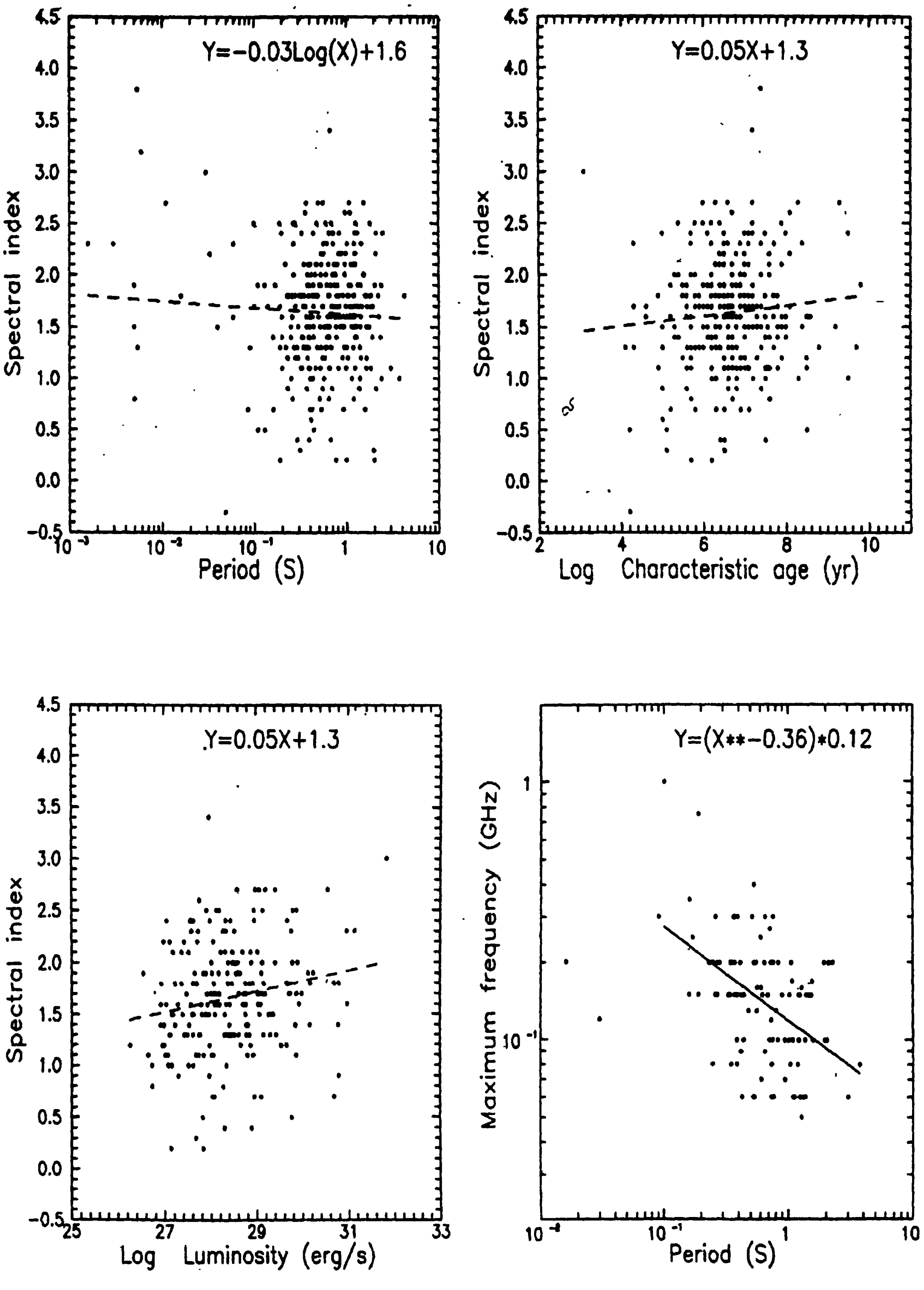
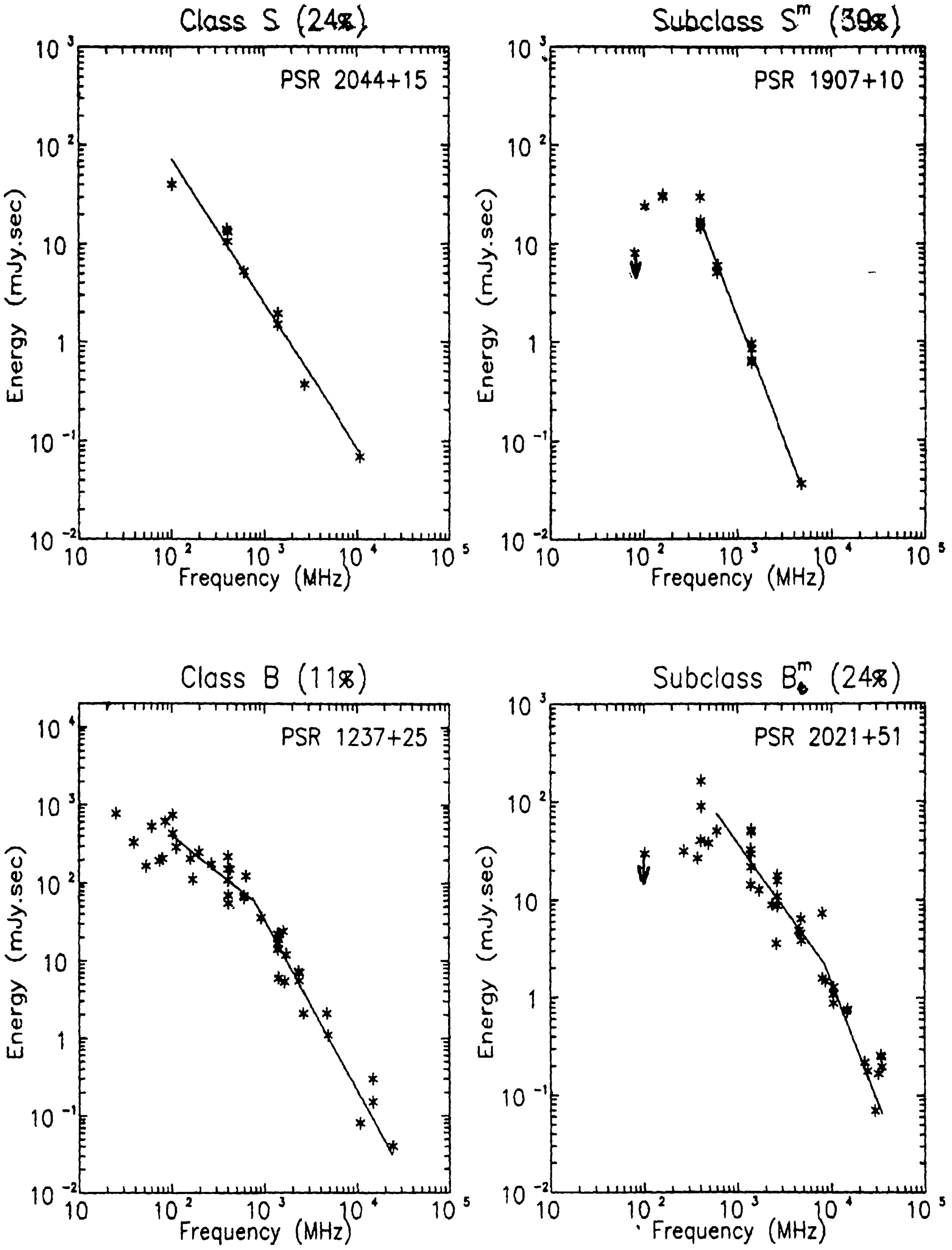


Figure 2. Plots showing the correlations of spectral index versus period, characteristic age and integral luminosity. The correlation between maximum frequency versus period for the 114 pulsars.



Class S (24%)

Subclass S^m (39%)

Class B (11%)

Subclass B_t^m (24%)

Figure 3. The examples of two main classes of pulsar spectra S (PSR 2044+15) and B (PSR 1237+25) with subclasses S^m (PSR 1907+10), B_t^m (PSR 2021+51).

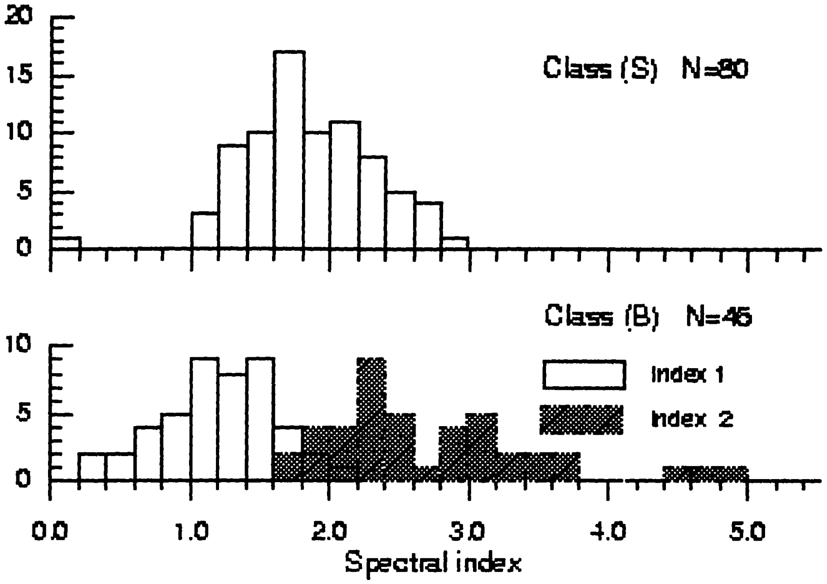


Figure 4. Distribution of spectral index α for class S (top) and distribution indices α_1, α_2 for class B (bottom). $\bar{\alpha} = 1.9$, $\sigma = 0.46$; $\bar{\alpha}_1 = 1.24$, $\sigma = 0.4$; $\bar{\alpha}_2 = 2.8$, $\sigma = 0.8$.

parameter (a), the height of emission region (h) and thin structure of magnefic field in this region (t.s.B). The first step needs to be to understand how spectra of different components depend on the last three parameters for one pulsar. On the basis of this understanding it is necessary to investigate correlations with other parameters, to find the mechanism of pulsar radio emission.

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