Astron. Astrophys. 352, 489–494 (1999)

ASTRONOMY
AND
ASTROPHYSICS

Unusual frequency dependence of the width of integrated profiles of millisecond pulsars

A.D. Kuzmin and B.Ya. Losovsky

Pushchino Radio Astronomical Observatory, Astro Space Center, Lebedev Physical Institute, Pushchino, Moscow Reg., 142292, Russia (akuzmin@prao.psn.ru)

Received 15 March 1999 / Accepted 6 September 1999

Abstract. We have performed a comparative analysis of the frequency dependence of the profile widths of millisecond and normal pulsars. In this study we combine our 102 MHz observations with data at higher frequencies borrowed from the literature. We find that the profile width of millisecond pulsars remains nearly constant in the frequency range between 102 and 1400 MHz. This is in contrast with what is known for much slower pulsars where typically the pulse profile narrows significantly at the same frequency range. Our findings indicate that the geometry of the radio emission region of millisecond pulsars differs from that of normal pulsars. We therefore suggest that either the magnetic field configuration in millisecond pulsar magnetospheres deviates from that of a pure dipole, or (and) the radio emission region is compressed.

Key words: stars: magnetic fields – stars: pulsars: general

1. Introduction

The frequency dependence of pulsar integrated profiles holds significant information on pulsar emission physics. In particular the narrowing of the profile width with increasing frequency, often observed at slow *normal* pulsars, has led many researchers to suggest that the magnetic field dominating the pulsar emission region has a purely dipolar structure. Furthermore, a radius-to-frequency mapping (RFM) is thought to exist in the magnetospheres of at least the normal pulsars. In this model the radio emission is closely related to the local plasma frequency, resulting in a stratification of the radio emission region. The high radio frequencies are emitted closer to the stellar surface while the lower frequencies are considered to emanate from further out. The integrated profile experiences a progressive narrowing as frequency increases (Komesaroff et al. 1970, Cordes 1978, Thorsett 1991). An alternative explanation attributes the observed low-frequency profile broadening to a propagation effect: the birefringence is assumed, with the whole spectrum emitted at the same altitude above the stellar surface. In this picture a RFM is not necessary (McKinnon 1997).

Millisecond pulsars are believed to be a special population of pulsars, which distinguish from normal pulsars by period, their first derivative, magnetic field strength, age and most importantly evolutionary history (Lyne & Smith 1990). One may expect that the radio emission characteristics of millisecond pulsars will be different from those of normal pulsars as well. However, it is only recently that comparative studies of the radio emission characteristics between millisecond and normal pulsars have appeared in the literature.

Manchester (1992) compared the pulse shape and polarization of two millisecond and two normal pulsars as well as the distribution of the observed radio luminosity. In this work Manchester concluded that the observed properties of the pulsed radio emission between the two pulsar populations are remarkably similar. Foster et al. (1991) studied the profile frequency dependence of four millisecond pulsars and concluded that in the frequency range between 425 and 3000 MHz no significant profile width narrowing is evident. Kuzmin & Losovsky (1996) performed 102 MHz observations of the millisecond pulsar PSR J2145–0705 and discovered an unusual frequency dependence of its profile. As shown by Kuzmin & Losovsky (1996) the width of the integrated profile of PSR J2157-0705 is nearly independent of frequency. Evidence is presented that the component separation of this pulsar profile even increases with frequency. Kramer et al. (1998) and Xilouris et al. (1998) presented a collection of 27 profiles of millisecond pulsars at 1.4 GHz including polarimetric observations. Comparing the frequency development of pulse profiles of normal and millisecond pulsars between 400 and 1400 MHz they showed that the development of the profiles of millisecond pulsars with frequency is rather slow, in stark contrast with what is known for normal pulsars.

These studies concentrate mainly on high radio frequencies, while there is a lack of data at lower radio frequencies. Low frequency radio observations are in particular difficult due to the scattering that the radio signals suffer as they propagate through the interstellar medium.

Kuzmin & Losovsky (1999) presented a collection of 20 millisecond pulsars at 102 MHz, which extends our knowledge of millisecond pulsar profiles to the lowest frequency where such observations have been performed so far. Based on these observations and higher frequency data we present in this work the results of an analysis of the frequency dependence of the inte-

Send offprint requests to: A. Kuzmin

grated profile width for 12 millisecond pulsars in the frequency range between 102 ÷ 1400 MHz. We compare our results with a sample of normal pulsars searching for similarities and differences between these two pulsar populations.

2. Observations and data reduction

The observations were performed at 102 MHz between 1991 and 1997 with the Large Phased Array BSA radio telescope of Pushchino Radio Astronomical Observatory. One linear polarization was received. A filter bank of 32 x 5 kHz filters was used for collecting the data allowing in this way sufficient dispersion removal. The sampling interval was set between 0.64 and 0.128 ms, depending on pulsar period P and dispersion measure DM. The actual resolution was limited by the dispersion broadening Δt_{DM} caused by the signal propagation through the interstellar medium.

Each integrated profile was formed by synchronous integration of individual pulses with the topocentric pulsar period during the 215/cosδ seconds passage of each source through the antenna beam width of the radio telescope, where δ is a declination of a source. All observations were time referenced to the Observatory rubidium master clock, which in turn was monitored against the National Time Standard via a TV timing signal. Ephemerides for timing observations were obtained from the catalogue by Taylor et al. (1993; 1995).

During the off-line data reduction the signal was cleaned from radio interference. Subsequently the dispersion delay imposed by the interstellar medium was removed. Several sessions were added together based on timing to increase the signal to noise ratio of the profiles and to reduce the influence of a polarization of pulsar radio emission as well. For profiles with good signal to noise ratio an additional time correction based on cross correlation was made.

Low frequency observations of millisecond pulsars are difficult to perform because the signal from the majority of these sources is heavily distorted by interstellar scattering. In order to reduce this distortion we have employed a technique developed by Kuzmin & Izvekova (1993), which is capable of compensating for interstellar scattering of low frequency profiles.

This method is based on the theory of pulse transients in communications circuits (e.g. Cherry 1949). The intrinsic pulse profile $x(t)$ is obtained by an inverse Fourier transformation of its spectrum $X(\omega)$

$$x(t) = 1/2\pi \int X(\omega) exp(j\omega t) d\omega, \quad (1)$$

while

$$X(\omega) = Y(\omega)/G(\omega). \quad (2)$$

The spectrum of the observed profile $Y(\omega)$ and the frequency response of a communication circuit $G(\omega)$ are found by a Fourier transformation of the observed profile $y(t)$ and the transfer characteristic of the communication circuit $g(t)$ as

$$Y(\omega) = \int y(t) exp(-j\omega t) dt, \quad (3)$$

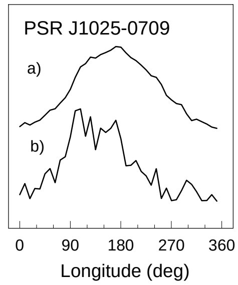

Fig. 1. Example of a descattering compensation of the millisecond pulsar PSR J1025-0709: a) observed profile b) compensated profile, $\tau_{comp} = 0.7$ ms.

$$G(\omega) = \int g(t) exp(-j\omega t) dt. \quad (4)$$

In our case the ISM plays the role of the communication circuit. We have assumed a simple *thin screen* model of scattering for which the transient characteristic is represented by truncated exponent

$$g(t) = \begin{cases} 0 \text{ for } t < 0 \\ exp(-t/\tau_{sc}) \text{ for } t \geq 0. \end{cases}$$

The value of scattering broadening τ_{sc} was derived from our observations. We utilize the procedure developed by Alurkar et al. (1986) for generating the modeled scattered profile by the scatter of a Gaussian template pulse and its least-squares fitting to the observed profile. The values of τ_{sc}, a width and a position of Gaussian template pulse were obtained as adjustable parameters by the fitting procedure. These τ_{sc} values include also the receiver circuit time constant. Therefore, the receiver circuit pulse broadening was corrected by the descattering procedure as well. An example of a descattering compensation for the millisecond pulsar PSR J1025–0709 is shown in Fig. 1. More details about the practical realization can be found in Kuzmin & Izvekova (1993).

In order to reduced the influence of the dispersion broadening we limited our analysis to 12 pulsars, for which dispersion broadening at 102 MHz $\Delta t_{DM} \leq 0.5 W_{10}$, where W_{10} is a width of the profile at 0.1 level.

The pulsars in our sample together with their period P, dispersion measure DM, the values of the dispersion broadening Δt_{DM} (in milliseconds and degrees of the longitude), the descattering compensation τ_{comp} (in milliseconds) and a signal to noise ratio S/N are presented in Table 1.

3. Analysis and results

For the analysis of the profile frequency dependence we combine our 102 MHz profiles with high frequency data at several frequencies in the range between 400 and 1400 MHz. The data is taken from Bailes et al. (1997), Camilo et al. (1996), Foster et al. (1993), Foster et al. (1995), Gould & Lyne (1999), Kramer et al. (1998), Lorimer (1994), Lorimer et al. (1995), Nicastro et al. (1995), Nice et al. (1993), Nice et al. (1996), Sayer et al. (1997), Wolszczan & Frail (1992).

Table 1. Observational and reduction parameters.

PSR	P ms	DM pc cm^{-3}	Δt_{DM} ms	Δt_{DM} degrees	τ_{comp} ms	S/N
J1012+5307	5.25	9.0	0.34	23	1.0	17
J1022+10–	16.45	10.2	0.39	8.5	0.9	12
J1025–0709	5.16	6.4	0.24	17	0.7	8
B1257+12–	6.21	10.1	0.38	22	0.8	20
J1518+4904	40.93	11.6	0.44	3.9	-	15
B1534+12–	37.90	11.6	0.44	4.2	-	20
J1713+0747	4.57	15.9	0.61	48	0.5	10
J1730–2304	8.12	9.6	0.37	16	1.0	10
B1855+09–	5.36	13.3	0.51	34	1.0	12
J2019+2425	3.93	17.2	0.66	60	0.8	11
J2145–0750	16.05	9.0	0.34	7.6	-	85
J2322+2057	4.80	13.4	0.51	38	0.5	12

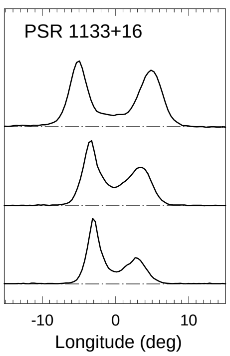

Fig. 2. Integrated profiles of normal pulsar PSR 1133 + 16 at frequencies 102 MHz (top line), 406 MHz (middle line) and 1380 MHz (bottom line). Alignment is arbitrary.

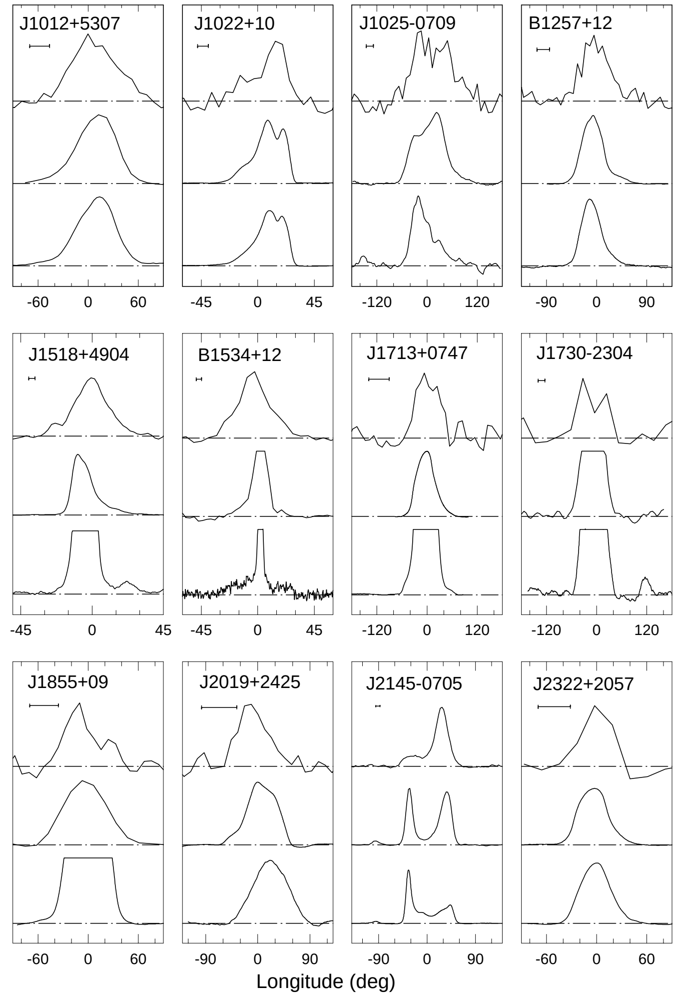

Fig. 3. Integrated profiles of millisecond pulsars at frequencies 102 MHz (top line), $\sim$ 400 MHz (middle line) and $\sim$ 1400 MHz (bottom line). High frequency profiles were smoothed out to obtain the same dispersion broadening, equal to that observed at 102 MHz (see text). Alignment is arbitrary. For pulsars PSR J1518+4904, B1534+12, J1713+0747, J1730+2304 and B1855+09 the high frequency profiles are shown in multiplied scale.

The initial analysis of the frequency dependence of the profile width was made qualitatively, by visual comparison of profiles. The multifrequency alignment was done visually by superposition of profiles.

A typical frequency development of the pulse profile for a normal pulsar is illustrated in Fig. 2. Here the integrated profiles of PSR 1133+16 at 102, 406 and 1380 MHz are plotted. As can be seen the profile narrows with frequency.

The frequency dependence of the integrated profiles of the millisecond pulsars in our sample at the same frequency range is shown in Fig. 3. The horizontal bars in this figure denote the actual resolution at 102 MHz, which was limited by the dispersion broadening Δt_{DM} as listed in Table 1. High frequency profiles are smoothed out to obtain the same dispersion broadening, equal to that observed at 102 MHz. As can be seen in this figure, the profile width of millisecond pulsars at a near zero level remains roughly constant with frequency.

In order to quantify our analysis we employed the component separation method, outlined by Foster et al. (1991), Wu et al. (1992), and further elaborated by Kramer et al. (1994) and Kuzmin & Izvekova (1996). The integrated profile was decomposed into several Gaussian-shaped individual components

$$x(\phi) = \Sigma a_i exp[-ln2((\phi - \phi_i)/w_i)^2], \quad (5)$$

where a_i, w_i and ϕ_i denote the intensity, half-power width and pulse phase respectively of the components. The analytical profile $x(\phi)$ was compared with the observed one in order to obtain the residual level between these two. This was done by means of a least square iterative fitting procedure resulting in values of a_i, w_i and ϕ_i that match the observed and analytical profiles best. As a criterion for the number of Gaussian components we required that the residuals (the difference between the observed and the analytical profiles) should be comparable to the off-pulse noise, similar to the method explained in Kramer et al. (1994). This means that the residuals should not have any regular component-like structures, which exceed the off-pulse noise. The residual noise level should be comparable to that of the off-pulse noise. To set a uniform condition in our analysis, we strove for the decomposition into the same number of Gaussian components at each frequency.

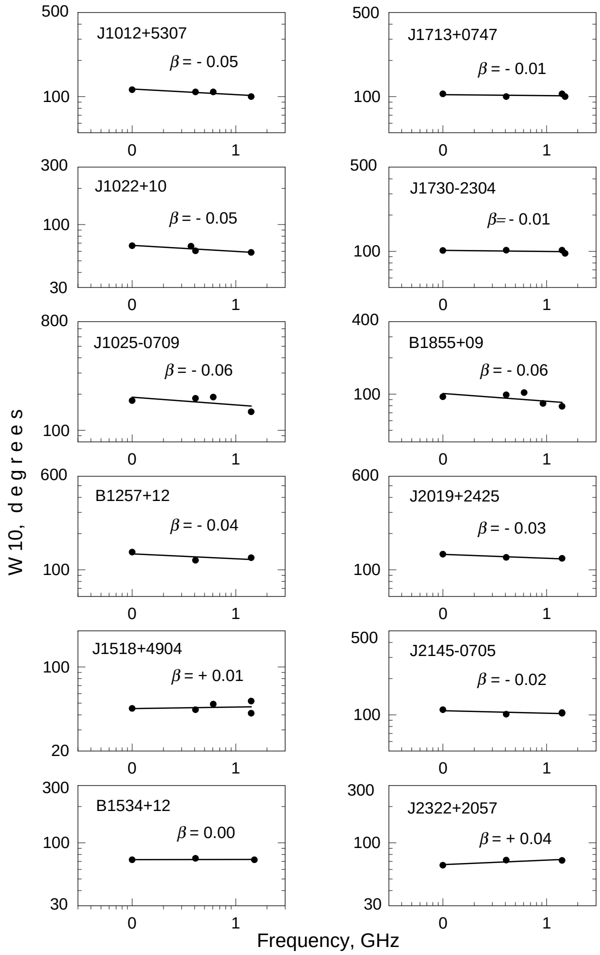

Fig. 4. Frequency dependence of the width of integrated profiles of millisecond pulsars. Solid lines represent the results of a power law fit to the data. The index resulting from this regression is also presented for each pulsar.

We refer the widths of the integrated profiles to the 10% level of the peak intensity of the leading and the trailing profile components.

$$W_{10} = \phi^{trail} - \phi^{lead} + 1/2(w_{10}^{trail} + w_{10}^{lead}). \quad (6)$$

Here ϕ^{lead}, ϕ^{trail}, w_{10}^{lead} and w_{10}^{trail} are pulse phases and widths of the leading and trailing components (at 10% level). The frequency dependence of the profile widths of millisecond pulsars are presented in Fig. 4.

In our quantitative analysis we have approximated this dependence with power low $W_{10}(f) \propto f^{\beta}$ similar to Thorsett (1991). The value of the exponent β, its regression error σ_{β} and a reference for sources of the information on high-frequency profiles are presented in Table 2. The mean value of β is $\bar{\beta} = -0.02$ with a standard deviation 0.03.

A similar profile analysis was performed for a sample of 27 normal pulsars from the catalogue of Kuzmin et al. (1998) and also Izvekova et al. (1993). The mean value of β for normal pulsars is $\bar{\beta} = -0.17$ with a standard deviation 0.08. It should be noted that low frequency 102 MHz observations of normal pulsars were performed with the same Large Phased Array BSA radio telescope in Pushchino Radio Astronomy Observatory.

Table 2. Frequency dependence of the profile's width

PSR	P,ms	β	σ_{β}	Ref
J1012+5307	5.25	–0.05	0.01	1,2
J1022+10–	16.45	–0.05	0.02	2,3,4
J1025–0709	5.16	–0.06	0.07	2,5
B1257+12–	6.21	–0.04	0.04	2,6
J1518+4904	40.93	+0.01	0.05	2,7
B1534+12–	37.90	+0.00	0.01	2,13
J1713+0747	4.57	–0.01	0.01	2.11
J1730–2304	8.12	–0.01	0.01	2,12
B1855+09–	5.36	–0.06	0.05	2,8
J2019+2425	3.93	–0.03	0.01	2,9
J2145–0750	16.05	–0.02	0.02	2,10
J2322+2057	4.80	+0.04	0.02	2,9

References: 1 -Nicastro et al. (1995); 2 -Kramer et al. (1998); 3 -Sayer et al. (1997); 4 -Camilo et al. (1996); 5 -Bailes et al. (1997); 6 -Wolszczan & Frail (1992); 7 -Nice et al. (1996); 8 -Gould & Lyne (1999); 9 -Nice et al. (1993); 10 -Lorimer (1994); 11 -Foster et al. (1993); 12 -Lorimer et al. (1995); 13 -Foster et al. (1995).

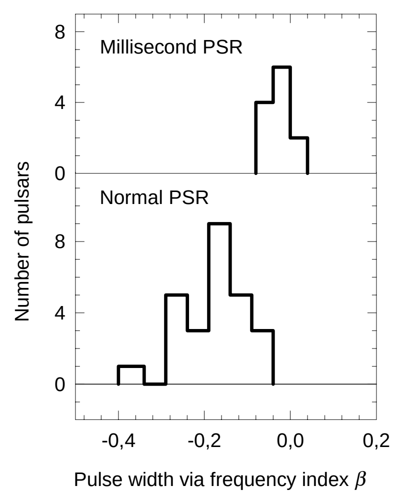

Fig. 5. Distribution of β indices of the frequency dependence of the integrated profile width of millisecond and normal pulsars.

The comparison of the indices β of the profile frequency dependence between millisecond and normal pulsars is presented in Fig. 5. As can be seen in this figure there is an obvious difference between these two distributions. The statistical test confirms that these are two different populations (Kolmogorov-Smirnov test yields a probability of 0.1% that they are drawn from the same parent distribution).

Thus, the frequency dependence of the width of integrated profiles of millisecond pulsars is much weaker, than that of normal ones.

4. Discussion

An indication that the profile development of millisecond pulsars is rather slow has already been suggested by Foster et al.

(1991), Kuzmin & Losovsky (1996), Kramer et al. (1998) and Xilouris et al. (1998). In this work we extend the frequency range of previous studies towards the lowest frequencies ever observed.

Our main conclusion is that the weak frequency dependence of the profile width detected in millisecond pulsars is a typical feature of their radio emission. This indicates that millisecond pulsar emission regions do not simply represent scaled versions of the emission regions of normal pulsars, as already pointed out by other authors.

The radius of the light cylinder of millisecond pulsars is much smaller than for normal ones. This means that an emission region is located closer to the stellar surface than in normal pulsars. This may modify the magnetic field dominating the radio emission region altering its configuration from a pure dipole to a higher order multipole (Davies et al. 1984, Kuzmin et al. 1986). Alternatively, the emission region could simply be radially compressed and hence more compact (Kramer et al. 1998).

Multipole components near the stellar surface have been assumed by Ruderman & Sutherland (1975) for the production of electron-positron pairs in the polar gap region. Davies et al. (1984) and Kuzmin et al. (1986) suggested the multipole components for the interpretation of pulse phase misalignments of integrated profiles at high frequencies. Krolic (1991) noted that a number of millisecond pulsars indeed show complicated pulse structure and suggested that this may be taken as evidence of multipole magnetic fields. Ruderman (1991) and Chen & Ruderman (1993) assumed that unusual magnetic field configuration may occur because of the recycling process during their evolution.

An example of superposition of a dipole and quadrupole magnetic field, which may have a small divergence of the magnetic field lines and produce a weak frequency dependence of the width of integrated profiles is illustrated in Fig. 5 in Kuzmin & Losovsky (1996).

Kramer et al. (1998) and Xilouris et al. (1998) proposed that the rather slow development of the profiles with frequency suggests very compact magnetospheres. We believe that this version can be considered as alternative explanation. A small radius of light cylinder $r_{LC} = cP/2\pi$ will "compress" geometrically the emission region. Therefore, the altitude of an emitting level depends on frequency much less than in normal pulsars.

Multifrequency time alignment experiments spread over a wide frequency range are necessary to give further insight into the structure of the magnetic field in millisecond pulsars.

5. Conclusion

A study of 12 millisecond pulsar profiles at 102 MHz, the lowest frequency where millisecond pulsar observations have been conducted so far, indicates a very weak frequency dependence of their profiles. This is much weaker than what is typically observed for normal pulsars and is in good agreement with what is known for millisecond pulsars from higher frequencies. This suggests that the geometry of the emission region of millisecond pulsars is unlike that of normal ones. We suggest that the magnetic field configuration in the emission regions of millisecond pulsars is distorted from a dipolar configuration. Alternatively, the emission region could simply become radial compressed, making it observationally difficult to distinguish any changes as a function of frequency. A thorough multifrequency study of time aligned profiles covering the widest frequency range possible is needed to probe the magnetic field configuration further.

Acknowledgements. We are grateful to an anonymous referee for valuable comments. The work was partially supported by Russian Foundation of Basic Research (project N 98-02-17532) and INTAS (project N 96-0154). The integrated profiles at frequencies 370÷1530 MHz were obtained through the European Pulsar Network of Max-Plank-Institut für Radioastronomie (Germany).

References

Alurkar S.K., Slee O.B., Borba A.D., 1986, Aust. J. Phys. 39, 433
Bailes M., Johnston S., Bell J.F., et al., 1997, ApJ 481, 386
Camilo F., Nice D.J., Shrauner J.A., et al., 1996, ApJ 469, 819
Chen K., Ruderman M.A., 1993, ApJ 408, 179
Cherry C., 1949, Pulses and Transients in Communication Circuits. Chapman & Hall, London
Cordes J.M., 1978, ApJ 222, 1006
Davies J.G., Lyne A.G., Smith F.G., et al., 1984, MNRAS 211, 57
Foster R.S., Fairhead L., Backer D.C., 1991, ApJ 378, 687
Foster R.S., Wolszczan A., Camilo F., 1993, ApJ 410, L91
Foster R.S., Cadwell B.J., Wolszczan A., et al., 1995, ApJ 454, 826
Gould D.M., Lyne A.G., 1999, MNRAS (in press)
Izvekova V.A., Kuzmin A.D., Lyne A.G., et al., 1993, MNRAS 261, 865
Komesaroff M.M., Moris D., Cooke D.J., 1970, ApJ 5, L37
Kramer M., Wielebinski R., Jessner A., et al., 1994, A&AS 107, 515
Kramer M., Xilouris K.M., Lorimer D.R., et al., 1998, ApJ 501, 270
Krolic J.H., 1991, ApJ 373, L69
Kuzmin A.D., Izvekova V.A., Malofeev V.A., et al., 1986, A&AS 161, 183
Kuzmin A.D., Izvekova V.A., 1993, MNRAS 260, 724
Kuzmin A.D., Izvekova V.A., 1996, Astronomy Letters 22, 439
Kuzmin A.D., Losovsky B.Ya., 1996, A&A 308, 91
Kuzmin A.D., Izvekova V.A., Shitov Yu.P., et al., 1998, A&AS 127, 355
Kuzmin A.D., Losovsky B.Ya., 1999, Astronomy Reports 43, 288
Lorimer D.R., 1994, Ph.D. Thesis, The University of Manchester
Lorimer D.R., Nicastro L., Lyne A.G., et al., 1995, ApJ 430, 933
Lyne A.G., Smith F.G., 1990, In: Pulsar Astronomy. Cambridge Univ. Press, p. 128
Manchester R.N., 1992, IAU Symposium N128, In: Hankins T.H., Rankin J.M., Gil J.A. (eds.) Magnetospheric Structure and Emission Mechanisms of Radio Pulsars. Pedagogical Univ.Press, Poland, Zielona Gora, p. 204
McKinnon M.M., 1997, ApJ 475, 763
Nicastro L., Lyne A.G., Lorimer D.R., et al., 1995, MNRAS 273, L68
Nice D.J., Taylor J.H., Fruchter A.S., 1993, ApJ 402, L49
Nice D.J., Sayer R.W., Taylor J.H., 1996, ApJ 466, L87
Ruderman M.A., Sutherland P.G., 1975, ApJ 196, 51
Ruderman M.A., 1991, ApJ 382, 576
Sayer R.W., Nice D.J., Kaspi V.M., 1997, ApJ 461, 357

Taylor J.H., Manchester R.N., Lyne A.G., 1993, ApJS 88, 529
Taylor J.H., Manchester R.N., Lyne A.G., et al., 1995, Catalog of 706 pulsars. Unpublished work
Thorsett S.E., 1991, ApJ 377, 263
Wolszczan A., Frail D.A., 1992, Nat 355, 145
Wu Xinji, Xu Wen, Rankin J.M., 1992, In: Hankins T.H., Rankin J.M., Gil J.A. (eds.) IAU Symposium No. 128, Magnetospheric Structure and Emission Mechanisms of Radio Pulsars. Pedagogical Univ.Press, Poland, Zielona Gora, p. 172
Xilouris K.M., Kramer M., Jessner A., et al., 1998, ApJ 501, 286