The structure of radio pulsars with interpulses

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There are known about 50 pulsars with interpulse radiation components located between the main pulses. The previously developed methods for determining the angle β between the rotation axis and the magnetic moment of the neutron star were used for the investigation of magnetosphere geometries in these objects. Our results let to confirm the previous assumption on two types of the pulsars with interpulses - aligned and orthogonal. Estimates of the age of the pulsars in these two groups showed that the aligned rotators several times older than the orthogonal objects.

We used the polar cap model for radio pulsars. In this model the geometry of radio pulsar depends on three parameters:

β —the angle between the rotational axis and the magnetic moment vector;

ζ — the angle between the rotational axis and the line of sight;

θ — the angular radius of the emission cone at this level of the magnetosphere.

I. LINE OF SIGHT PASSING THROUGH THE CENTER OF THE EMISSION CONE

The solution of this problem seems to be simplest when the line of sight passes through the center of the emission cone (β = ζ). In this case we can use the formula for the calculation of the angle β:

$$\sin\beta = \frac{\sin(\theta/2)}{\sin(W_{10}/4)} \, . \qquad (1)$$

We used the values of the angle θ, which were obtained in [1]:

$$sin\theta = f(\beta)(r/r_{LC})^{1/2} = 0{,}1565 f(\beta)/(B_{12}P)^{1/4}, \qquad (2)$$

here r — the distance between the radiation area and the center of the neutron star, r_{LC} — the light-cylinder radius, and

$$f(\beta) = \frac{\sqrt{2^{1/2}[cos\beta(9-sin^2\beta)^{1/2} + sin^2\beta](9-sin^2\beta)^{3/4}}}{3\sqrt{3^{1/2}[(9-sin^2\beta)^{1/2} - cos\beta]^{1/2}}} \, . \qquad (3)$$

If substitute (2) and (3) into (1) we can get the equation for calculation of the angle β with the free parameter r. It is possible to estimate the level of the radiation at the setting frequency generation, for which the values W_{10} are known.

There is the two-stream instability in pulsar magnetospheres. It means that there are primary beam with Lorentz factor $\gamma_b = 10^6$—10^7 and the secondary electron-positron plasma with $\gamma_p = 10$—10^3 and with the density several times higher than the primary beam. If we take it into account, we can obtain the equation for β:

$$\frac{[1-(1-sin^2\theta)^{1/2}]^{1/2}}{\sqrt{2}sin\beta} = \sin(W_{10}/4) \, . \qquad (4)$$

The data from [2, 7-14] had been used. There are profiles at 20 cm length, and the data on the swing of the position angle ψ(Φ) for some pulsars. It enabled us to estimate the width of the profile W_{10} and maximum derivative dψ/dΦ. The estimates obtained are shown in Table as β_1.

II. USING THE POLARIZATION DATA

In the model which was used the dependence of the position angle of linear polarization ψ of the longitude Φ described by the formula:

$$tg\psi = \frac{sin\beta sin\Phi}{cos\beta sin\zeta - sin\beta cos\zeta cos\Phi} \, . \qquad (5)$$

The maximum derivative of the position angle is reached at the center of the profile, and it is equal to

$$C = \left|\frac{d\psi}{d\Phi}\right|_{max} = \frac{\sin\beta}{\sin(\zeta-\beta)} \, . \qquad (6)$$

If we take into account the equation (2), we can estimate the angle β:

$$sin\beta <= \frac{0{,}1565 C f(\beta)}{(PB_{12})^{1/4}} \, . \qquad (7)$$

The resulting values of β (denoted β_2) are listed in Table.

III. THE CALCULATION OF THE ANGLE β USING THE PROFILE WIDTH AND THE MAXIMAL DERIVATIVE OF THE POSITION ANGLE

There is another possibility to estimate the angle β using the equation:

$$cos\theta = cos\beta cos\zeta + sin\beta sin\zeta \cos(W_{10}/2) \qquad (8)$$

for β, ζ and θ. Two other equations can be (2) and (6). (6) can be written as:

$$tg\beta = \frac{C(1-cos^2\zeta)^{1/2}}{1+Ccos\zeta} \, . \qquad (9)$$

Solving this system with respect to θ, ζ and β, we obtain the values of the angle β, listed in the table and called β_3.

Calculations are made with C> 0 and C <0. There is a solution for some values of C only if C <0.

IV. APROXIMATION OF OBSERVED VALUES OF THE POSITION ANGLE BY THE MODEL CURVE

The polarization measurements in the main pulse and the interpulse were carried out for a number of pulsars. For such objects we can use the dependence (5) with different values of β and ζ to get the most probable value of β by fitting this dependence to observed points ψ(Φ). This approximation has been repeatedly held by other authors (see, eg, [15, 16]), but for some objects we have done it for the first time (Fig. 2). The corresponding values of the angle β_4 are shown in Table in bold.

Regardless the direction of the neutron star rotation, if the signs of the derivatives of C_1 (Φ=180º) and C (Φ=0º) are identical, then ζ<β, ie the line of sight is closer to the axis of rotation. And when ζ>β the signs of C_1 and C will be different. The both positive derivatives indicate the opposite rotation of the neutron star. This conclusion is used by us when we fit the model curves to the observed swing of the position angle. It is possible to fit a curve separately in the main pulse and in the interpulse. We did this for a number of pulsars (Fig. 3).

V. USING OF ADDITIONAL ARGUMENTS TO ESTIMATE THE ANGLE β

If the magnetic moment is orthogonal to the rotation axis the distance between the MP and the IP should be very close to 180º and it should not depend on the frequency. In the case of aligned pulsar distance MP-IP may be any and may depend on the frequency.

According to our data aligned pulsars are those in which the distances MP-IP more than 10º different from 180º and/or estimates of the angle β give less than 30º: PSR J0828-3417, 0831-4406, 0834-4159, 0953+0755, 1057-5226, 1244-6531, 1424-6438, 1627-4706, 1637-4450, 1737-3555, 1806-1920, 1808-1726, 1825-0935, 1851+0418, 1852-0118, 1903+0925, 1932+1059, 1946+1805, 2032+4127. The orthogonal pulsars are PSR J0842-4851, 0908-4913, 1107-5907, 1126-6054, 1413-6307, 1549-4848, 1637-4553, 1705-1906, 1722-3712, 1739-2903 with high values of the angle β and distances MP-IP is not very different from 180º.

The largest disagreements of belonging to the aligned or orthogonal objects exist for the PSR B0950+08 (J0953+0755), B1055-52 (J1057-5226) and B1822-09 (J1825-0935). According to our data all of them belong to aligned rotators.

VI. CONCLUSIONS

The great interest is the estimate of the age of the objects within each of the groups. For this purpose we used characteristic age τ = P/(2dP/dt), distance |z| of the pulsar from the galactic plane and its luminosity L. Each of these has its drawbacks. But in average, they reveal the correct trends. For 19 aligned and 10 orthogonal pulsars listed in the previous section the catalog [6] gives the value τ, z and L.

Two groups are characterized by the following average values:

β < 30º:	*β > 60º:*
<logτ> = 6.35 ± 1.06,	*<logτ> = 5.59 ± 1.12,*
<logL> = 1.50 ± 0.47,	*<logL> = 2.25 ± 0.53,*

The median values are:

β < 30º:	*β > 60º:*
τ = 3.8 × 10⁶ years,	*τ = 7.5 × 10⁵ years,*
*L = 40.0 mJy kpc², *	*L = 188.5 mJy kpc²,*

The resulting mean scores and median values of ages show that the orthogonal pulsars are in several times younger than aligned.

RESULTS

1. The estimates of the angle β between the magnetic moment of the neutron star and the rotation axis were made using our methods for 42 radio pulsars with interpulses.
2. It is shown that pulsars with interpulses divide into two groups. One of them contains objects with nearly orthogonal axes (10 pulsars) and another - rotators with nearly aligned axes (19 sources). To verify the membership of 13 pulsars it is necessary to accumulate new polarization data.
3. Using the characteristic age, luminosity and z-distances of pulsars we estimated their ages. It turned out that the orthogonal rotators are younger systematically than aligned ones. This conclusion requires confirmation based on new data, since the evolution of the inclination angle

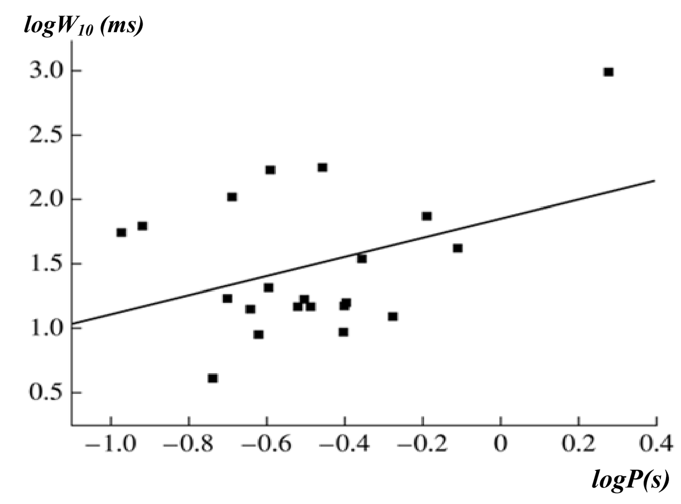

Fig. 1. Dependence of the pulse width on the period pulsar for pulsars with interpulses from the catalog [6].

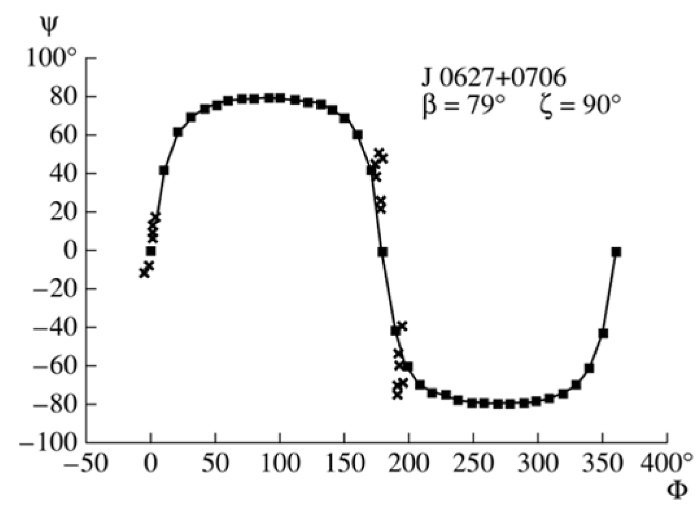

Fig. 2. The model curve for the pulsar J0627 +0706. Crosses show the measured values of the position angle.

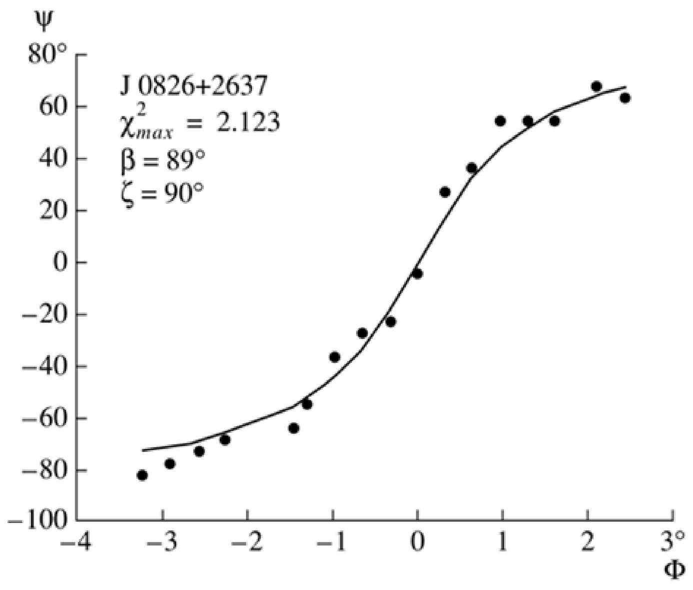

Fig. 3. The example of the approximation model curve for the position angle swing in the main pulse of the pulsar B0823 +26.

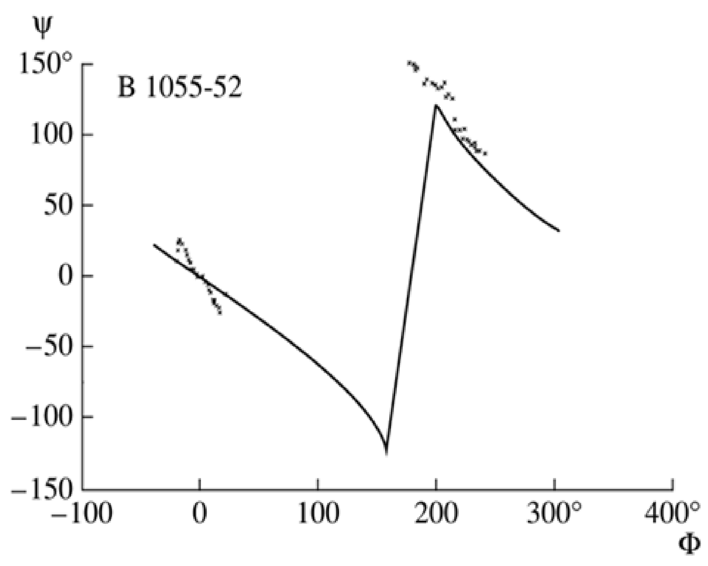

Fig. 4. The presentation of the model swing of the position angle ψ in pulsar B1055-52 at β = 6.8 ◦ and ζ = -5.0 ◦ (solid curve) with the measured values of ψ (crosses).

№	Pulsar (J…)	P, s	W_{10}, deg	C	B_{12}	r/R_*	β_1	β_2	β_3		β_4
									C>0	C<0	
1	0627+0706	0.48	7.2	5.85	7.68	29	74.4	37.4	40.6	73.7	**79**, 86 [2]
2	0826+2637	0.531	6.9	10	1.93	61	119.3	79.2	41.1	65.3	<89.5> (compilation in [3])
3	0828-3417	1.849	132	0.8	2.74	96	2.5	4.8		22.2	10 [4]
4	0831-4406	0.312	19.6		1.28	58	35.5				-
5	0834-4159	0.12	33.8		1.48	33	22.8				-
6	0842-4851	0.644	8.6		5	42	58.4				-
7	0905-5127	0.346	14.9	1.7	5.94	28	29.5	12.7	35.1	23.0	-
8	0908-4913	0.107	20	3.3	2.58	24	24.0	40.2	39.2	27.2	96[5]
9	0953+0755	0.253	30.3	2	0.49	84	29.5	30.0	36.4	24.2	**18.9** <7.3> [4, 6, 7]
10	1057-5226	0.197	34.2	1.7	2.18	35	17.4	18.8	35.4	23.3	**6.8**
11	1107-5907	0.253	26.3		0.0966	189	71.6				-
12	1126-6054	0.203	24.8		0.48	76	42.8				-
13	1244-6531	1.55	6	3.8	6.74	56	65.9	18.9	41.0	83.4	-
14	1413-6307	0.395	10.2		3.46	40	63.3				-
15	1424-6438	1.02	31.1		1	118	15.2				-
16	1549-4848	0.288	16.8	17.2	4.08	31	30.3	73.0	52.4	55.0	90[2]
17	1611-5209	0.182	7.4	13.2	1.97	36	127.7	98.7	46.2	62.2	-
18	1613-5234	0.66	39.7		4.22	46	9.0				-
19	1627-4706	0.14	69.2		1	44	11.1				-
20	1637-4450	0.25	47.1		0.77	67	15.3				-
21	1637-4553	0.119	20.4	16.1	1.25	36	49.6	104.4	42.4	60.1	-
22	1705-1906	0.299	17	7	2.26	43	36.2	65.4	42.3	70.4	-
23	1713-3844	1.6	8.8		34	25	20.5				-
24	1722-3712	0.236	13.9	7.1	3.24	32	47.0	65.0	41.5	70.2	**82**, 90.7 [2]
25	1737-3555	0.398	8	0.35	3.16	42	100.1	3.0	16.4	12.4	-
26	1739-2903	0.323	14.9	11.3	3.22	37	37.5	85.0	43.3	63.6	**80**, 84.2 [2]
27	1806-1920	0.88	86.8		0.25	219	7.9				-
28	1808-1726	0.24	166.2		0.11	173	7.5				-
29	1825-0935	0.769	21.7	1.8	12.86	29	12.1	9.1	35.6	16.6	**9**
30	1842+0358	0.23	11.1		0.88	60	114.5				-
31	1843-0702	0.19	19.2		1.3	45	44.3				-
32	1849+0409	0.76	9.7		8.2	36	36.5				-
33	1851+0418	0.29	112.2	0.5	1.13	59	5.6	5.9		16.6	-
34	1852-0118	0.45	37.2		1.8	58	13.3				-
35	1903+0925	0.36	207.7		7.34	26	2.0				-
36	1913+0832	0.13	31.1		1.59	33	24.1				-
37	1915+1410	0.3	41.5		0.24	131	23.5				-
38	1932+1059	0.227	20.7	1	1.04	55	40.1	12.8	28.8		<26> (compilation in [3])
39	1946+1805	0.441	42.6	0.8	0.21	170	21.1	13.0	27.6	18.2	**5**
40	2023+5037	0.37	9.1	5	1.96	51	101.3	45.5	39.3	76.9	**66**
41	2032+4127	0.14	34.4	1.1	3.46	24	16.7	11.8		20.4	**5**
42	2047+5029	0.45	6.4		2.76	47	120.8				-

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