On X-ray emission of radio pulsars

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Abstract

Pulsars play a crucial astrophysical role as the highly energetic compact radio, X-ray, and gamma-ray sources. More than 2500 radio pulsars included in the supplemented ATNF Pulsar catalogue are currently known . These objects radiate mainly in the radio range, but gamma emission is detected in approximately 200 pulsars. At present there are detailed data for 61 radio pulsars emitting X-rays as was shown by Possenti et al. (A&A, 387, 993, 2002) and Prinz & Becker (arXiv: 1511.07713, 2015) (see Table 1).

We have carried out the comparison of some characteristics describing X-ray loud radio pulsars and ordinary radio pulsars. We exclude from the consideration anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs).

Table 1: Radio pulsars detected as X-ray emitters

		P	dP/dt	Rlum1400	B_s	dE/dt	B_lc	log L_x	log L_x	log L_γ	log L_calc
		ms		mJy× kpc²	G	erg/sec	G	(2-10 keV)	(0,1-2 keV)	erg/sec	erg/sec
1	J0030+0451	4,87	1,02E-20	0,06	2,25E+08	3,5E+33	1,83E+04	29,88		32,76	30,10
2	J0101-6422	2,57	5,16E-21	0,28	1,17E+08	1,2E+34	6,42E+04		30,04	32,58	30,78
3	J0117+5914	101,44	5,85E-15	0,94	7,80E+11	2,2E+35	7,00E+03	30,34	32,04		31,25
4	J0205+6449	65,72	1,94E-13	0,46	3,61E+12	2,7E+37	1,19E+05	34,08		34,38	33,43
5	J0218+4232	2,32	7,74E-20	8,93	4,29E+08	2,4E+35	3,21E+05	33,20		34,58	32,11
6	J0337+1715	2,73	1,77E-20		2,22E+08	3,4E+34	1,02E+05		30,71		31,22
7	J0358+5413	156,38	4,39E-15	23,00	8,39E+11	4,5E+34	2,06E+03	31,76			30,46
8	J0437-4715	5,76	5,73E-20	3,66	5,81E+08	1,2E+34	2,85E+04	30,19		31,69	30,60
9	J0534+2200	33,39	4,21E-13	56,00	3,79E+12	4,5E+38	9,55E+05	36,65		35,79	34,79
10	J0537-6910	16,12	5,18E-14	0,00	9,25E+11	4,9E+38	2,07E+06	36,11			34,99
11	J0538+2817	143,16	3,67E-15	3,21	7,33E+11	4,9E+34	2,34E+03	29,31			30,52
12	J0540-6919	50,57	4,79E-13	59,28	4,98E+12	1,5E+38	3,61E+05	36,93			34,22
13	J0543+2329	246,00	1,54E-14	21,90	1,97E+12	4,1E+34	1,24E+03		30,61		30,32
14	J0633+1746	237,10	1,10E-14		1,63E+12	3,2E+34	1,15E+03	29,33		34,50	30,23
15	J0659+1414	384,89	5,50E-14	0,31	4,66E+12	3,8E+34	7,66E+02	30,26			30,19
16	J0751+1807	3,48	7,79E-21	3,94	1,67E+08	7,3E+33	3,71E+04	31,29		32,40	30,50
17	J0826+2637	530,66	1,71E-15	1,02	9,64E+11	4,5E+32	6,05E+01	28,99			28,20
18	J0835-4510	89,33	1,25E-13	86,24	3,38E+12	6,9E+36	4,45E+04	31,86			32,77
19	J0922+0638	430,63	1,37E-14	5,08	2,46E+12	6,8E+33	2,89E+02		30,23		29,42
20	J0953+0755	253,07	2,30E-16	5,72	2,44E+11	5,6E+32	1,41E+02	28,62			28,45
21	J1012+5307	5,26	1,71E-20	1,57	3,04E+08	4,7E+33	1,96E+04	29,58			30,21
22	J1024-0719	5,16	1,86E-20	2,23	3,13E+08	5,3E+33	2,13E+04	29,09		31,78	30,27
23	J1044-5737	139,03	5,46E-14		2,79E+12	8,0E+35	9,73E+03		29,92		31,74
24	J1048-5832	123,67	9,63E-14	54,66	3,49E+12	2,0E+36	1,73E+04	32,40		35,25	32,16
25	J1057-5226	197,11	5,83E-15		1,09E+12	3,0E+34	1,33E+03	29,48		33,63	30,23
26	J1105-6107	63,19	1,58E-14	4,18	1,01E+12	2,5E+36	3,76E+04	33,55		35,18	32,40
27	J1112-6103	64,96	3,15E-14	28,35	1,45E+12	4,5E+36	4,95E+04		32,78	35,56	32,65
28	J1119-6127	407,96	4,02E-12	56,45	4,10E+13	2,3E+36	5,66E+03	33,13		35,78	31,97
29	J1124-5916	135,48	7,53E-13	2,00	1,02E+13	1,2E+37	3,85E+04	34,48		35,23	32,92
30	J1224-6407	216,48	4,95E-15	62,40	1,05E+12	1,9E+34	9,68E+02		31,28		30,02
31	J1301-6310	663,83	5,64E-14	0,23	6,19E+12	7,6E+33	1,98E+02		31,48		29,37
32	J1341-6220	193,34	2,53E-13	301,64	7,08E+12	1,4E+36	9,18E+03		31,85		31,90
33	J1420-6048	68,18	8,32E-14	28,53	2,41E+12	1,0E+37	7,13E+04	33,33		35,81	33,00
34	J1513-5908	151,25	1,53E-12	18,20	1,54E+13	1,7E+37	4,17E+04	35,32		34,85	33,06
35	J1600-3053	3,60	9,50E-21	8,10	1,87E+08	8,1E+33	3,77E+04		30,61	33,23	30,53
36	J1617-5055	69,36	1,35E-13		3,10E+12	1,6E+37	8,70E+04	34,31			33,19
37	J1658-5324	2,44	1,12E-20	0,54	1,67E+08	3,0E+34	1,08E+05		30,23	33,48	31,19
38	J1709-4429	102,46	9,30E-14	49,35	3,12E+12	3,4E+36	2,72E+04	32,58		35,93	32,43
39	J1730-2304	8,12	2,02E-20	1,50	4,10E+08	1,5E+33	7,17E+03		30,08		29,62
40	J1731-1847	2,34	2,54E-20	8,45	2,47E+08	7,8E+34	1,80E+05		30,64		31,61
41	J1744-1134	4,07	8,93E-21	0,48	1,93E+08	5,2E+33	2,68E+04	28,97		32,83	30,32
42	J1801-2451	124,92	1,28E-13	12,27	4,04E+12	2,6E+36	1,95E+04	33,37		34,60	32,27
43	J1803-2137	133,67	1,34E-13	269,10	4,29E+12	2,2E+36	1,68E+04	32,75			32,19
44	J1811-1925	64,67	4,40E-14		1,71E+12	6,4E+36	5,92E+04	34,93			32,81
45	J1816+4510	3,19	4,31E-20		3,75E+08	5,2E+34	1,08E+05		30,32		31,37
46	J1824-2452A	3,05	1,62E-18	60,50	2,25E+09	2,2E+36	7,40E+05	33,56			33,01
47	J1825-0935	769,01	5,25E-14	1,08	6,43E+12	4,6E+33	1,33E+02		30,20		29,12
48	J1826-1334	101,49	7,53E-14	27,37	2,80E+12	2,8E+36	2,51E+04	34,51			32,35
49	J1832-0836	2,72	8,28E-21	0,72	1,52E+08	1,6E+34	7,08E+04		29,75		30,90
50	J1846-0258	326,57	7,11E-12		4,88E+13	8,1E+36	1,31E+04	36,22			32,55
51	J1856+0113	267,44	2,08E-13	2,07	7,55E+12	4,3E+35	3,70E+03	33,14			31,32
52	J1911-1114	3,63	1,40E-20	0,57	2,28E+08	1,2E+34	4,48E+04		29,81		30,69
53	J1932+1059	226,52	1,16E-15	3,46	5,18E+11	3,9E+33	4,18E+02	29,60			29,32
54	J1939+2134	1,56	1,05E-19	161,70	4,09E+08	1,1E+36	1,02E+06	32,73		34,15	32,85
55	J1952+3252	39,53	5,84E-15	9,00	4,86E+11	3,7E+36	7,38E+04	33,16		34,82	32,68
56	J2017+0603	2,90	7,99E-21	0,98	1,54E+08	1,3E+34	5,94E+04		30,52	33,99	30,79
57	J2022+3842	48,58	8,61E-14		2,07E+12	3,0E+37	1,69E+05	31,68			33,53
58	J2124-3358	4,93	2,06E-20	0,61	3,22E+08	6,8E+33	2,52E+04	29,77		32,60	30,39
59	J2222-0137	32,82	5,80E-21		4,42E+08	6,5E+30	1,17E+02		28,76		26,96
60	J2229+6114	51,62	7,83E-14	2,25	2,03E+12	2,2E+37	1,39E+05	33,12		34,29	33,40
61	J2337+6151	495,37	1,93E-13	0,69	9,91E+12	6,3E+34	7,64E+02	31,46			30,35

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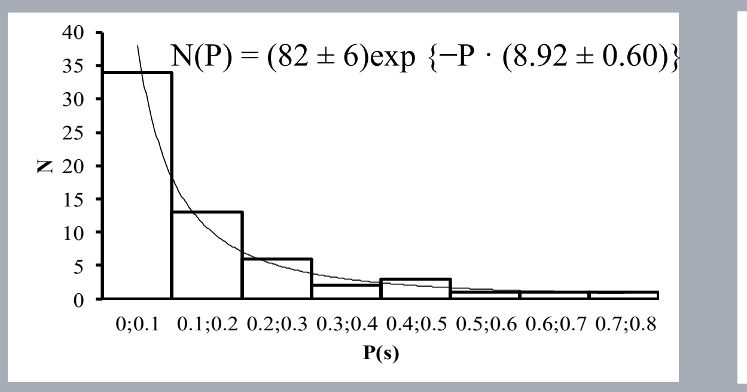
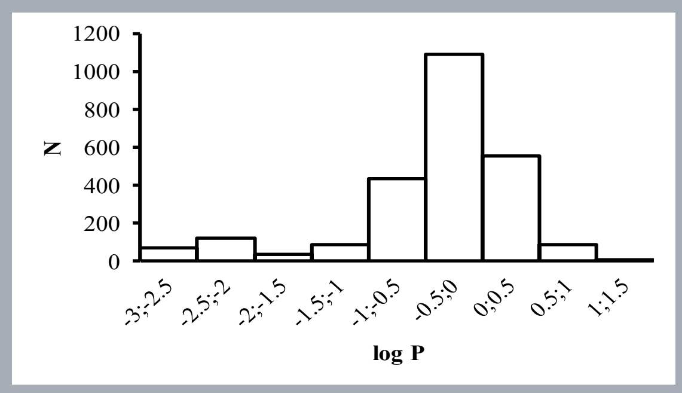
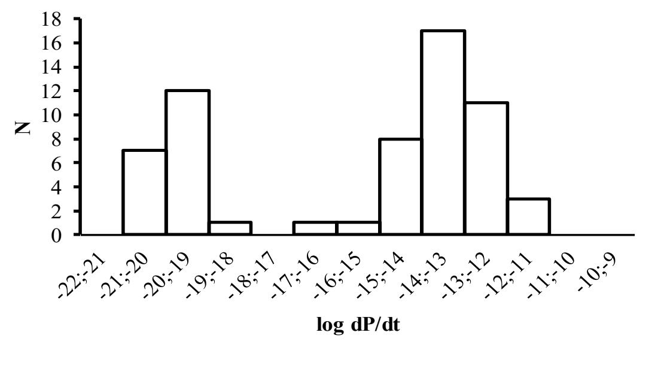
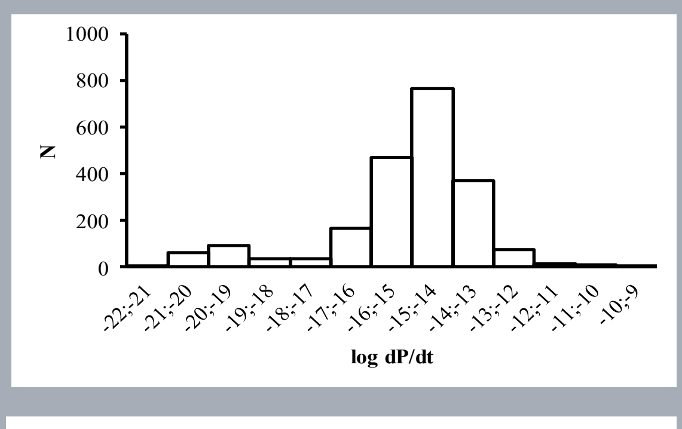
Distributions of main parameters



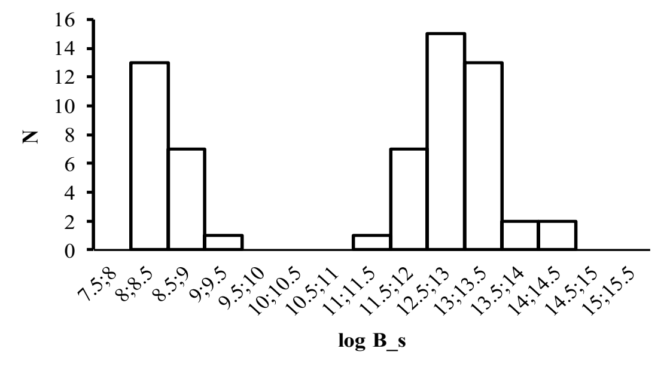


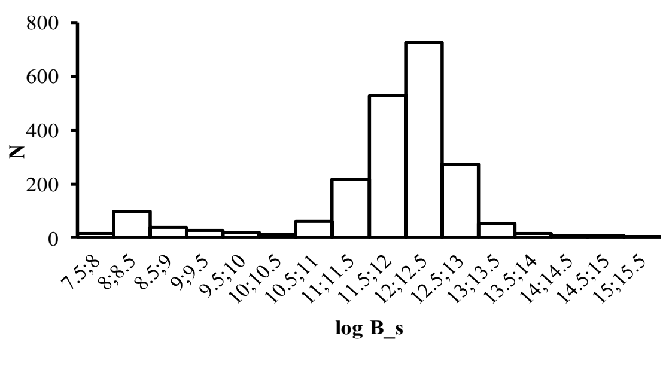
The majority of such pulsars has short spin periods with the average value < P > = 133 msec.



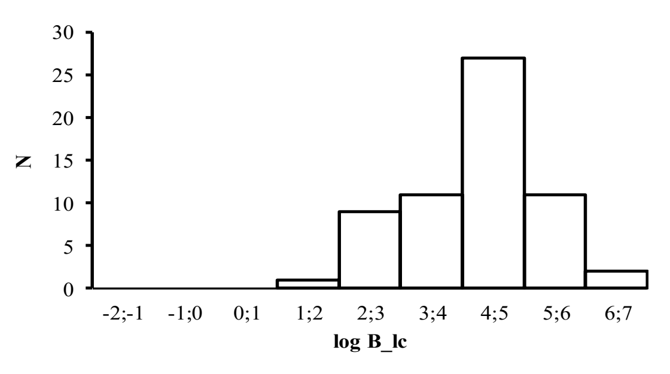


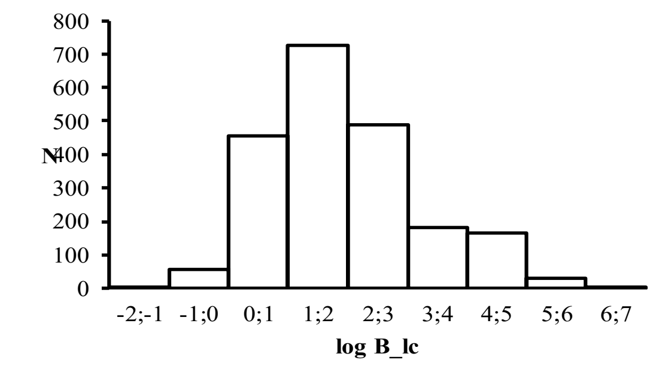
The distribution of period derivatives shows a bimodality. One of the groups contains millisecond (recycled) pulsars with < log dP/dt > = -19.69. Pulsars with long periods and < log dP/dt > = -13.61 belong to the second group.



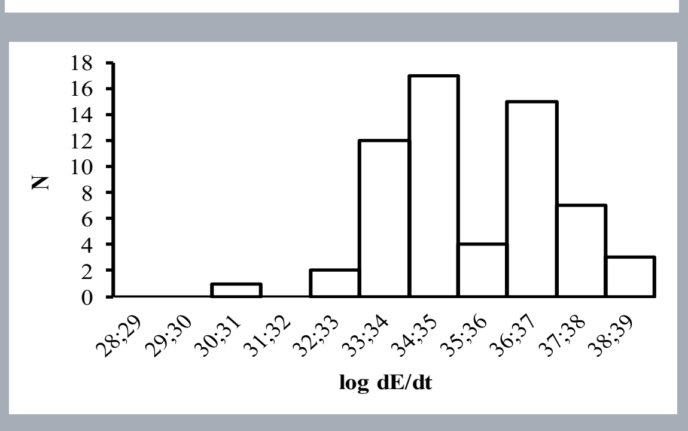


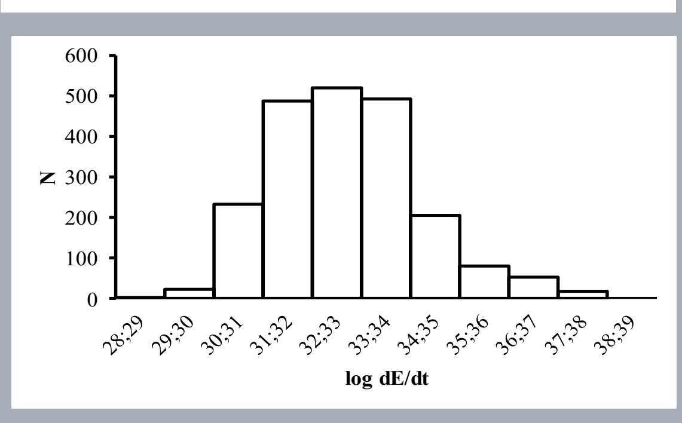
The similar bimodality is seen in the distribution of magnetic fields at the surface of the neutron star. The mean values of log B_s are 8.46 and 12.43 for millisecond and ordinary pulsars, respectively.





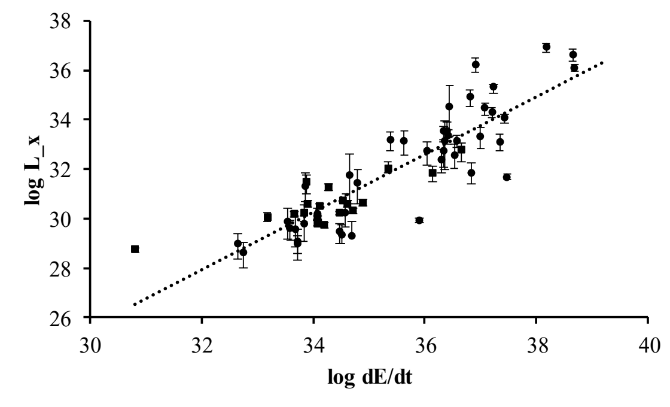
This distribution does not show the bimodality. The median value of <log B_lc> = 4.43 is three orders of magnitude higher than the values for radio pulsars without X-ray emission (<log B_lc> = 1.75).





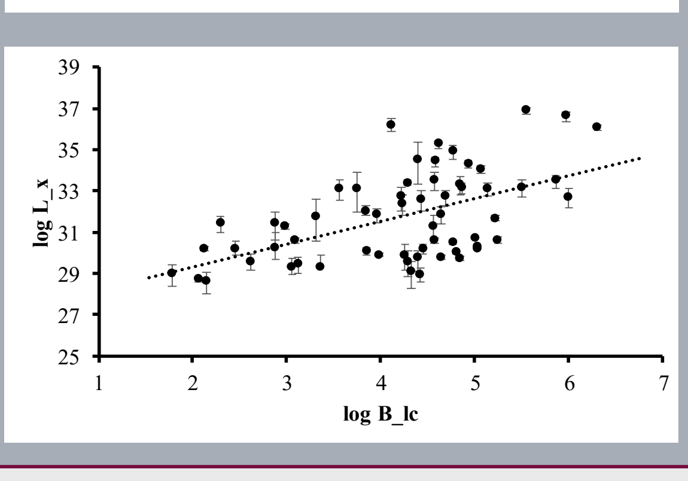
The rate of losses of rotational energy for pulsars considered(< log dE/dt> = 35.24) is also three orders of magnitude higher than the corresponding values for quiet pulsars. There is not a bimodality in the dE/dt distribution.

Some relationships between parameters of pulsars considered



Constructing this figure, we have used values of luminosities in the range: 2-10 keV from Possenti et al. (2002) (dots) and 0.1-2 keV from Prinz & Becker (2015) (squares). All the X-ray emission in the range 2-10 keV is non-thermal. For the diapason from 0.1 to 2 keV we have taken only the part of emission described by the power-law. It is caused by non-thermal mechanisms as well. As we can see, both ranges are well described by the unique dependences:

$$L_x = 3.47 \times 10^{-10} \left(\frac{dE}{dt}\right)^{1.17} \quad \log L_x = (1.17 \pm 0.08) \log \frac{dE}{dt} - 9.46 \pm 2.89$$

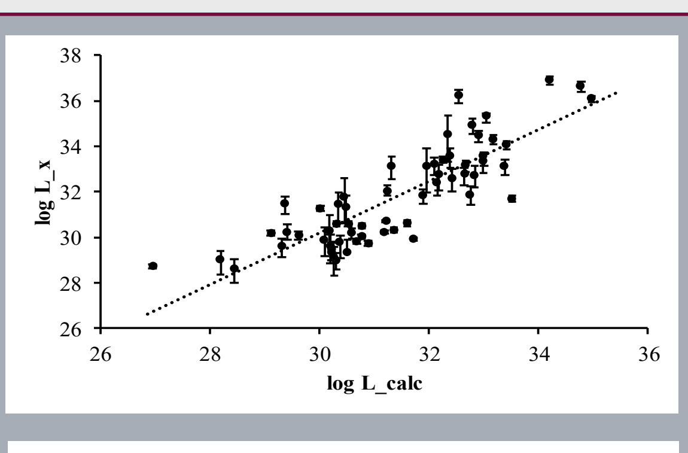


The argument for the conclusion on the generation of non-thermal X-ray emission at the periphery of the pulsar magnetosphere by the synchrotron mechanism is the correlation between the X-ray luminosity and the magnetic field near the light cylinder. The tendency of an increasing of L_x for higher values of magnetic fields at the light cylinder is detected. The corresponding relationship can be described as

$$\log L_x = (1.11 \pm 0.22) \log B_{lc} + 27.09 \pm 0.97$$

$$L_x = \frac{16\pi^8 R_*^8 I B_s^2 \gamma_r \psi^2 \frac{dP}{dt} \sin^2\beta}{m^3 c^{11} P^8} \qquad \psi = \frac{1}{2}\left(\frac{3\pi^3 m^5 c^7 \gamma_b^3}{4e^6 B^4 P^3 \gamma_p^4 \gamma_r^2}\right)^{1/4} \qquad L_{calc} = \frac{3^{1/2}\pi^{7/2} e I \frac{dP}{dt} \gamma_b^{3/2}}{32 c^{3/2} P^{7/2} m^{1/2} \gamma_p^2} = 10^{27} \frac{\left(\frac{dP}{dt}\right)_{-15}}{P^{7/2}}$$

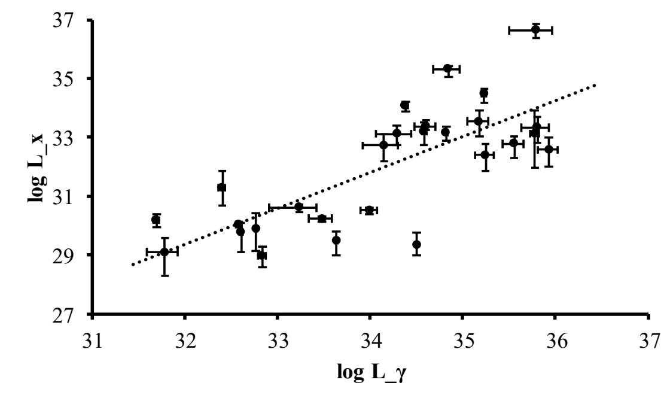
In these equations β is angle (in degrees) between magnetic moments and rotation axes, ψ is the pitch-angle of emitting electrons, γ_b is the Lorenz-factor of the primary beam, γ_p is the Lorenz-factor of the secondary electrons. There is no the detailed theory of outer regions of a pulsar magnetosphere, and we have used the suggestion of a dipolar structure of magnetic fields at any distances. In this case the dependence of L_{calc} on sinβ vanishes. However, in the real situation this dependence can appear and we must take it into account. The suggestion of the dipolar structure must be corrected when such theories will be worked out. We suggest also that $\gamma_b = 5 \cdot 10^6$, $\gamma_p = 10$ for all pulsars considered.

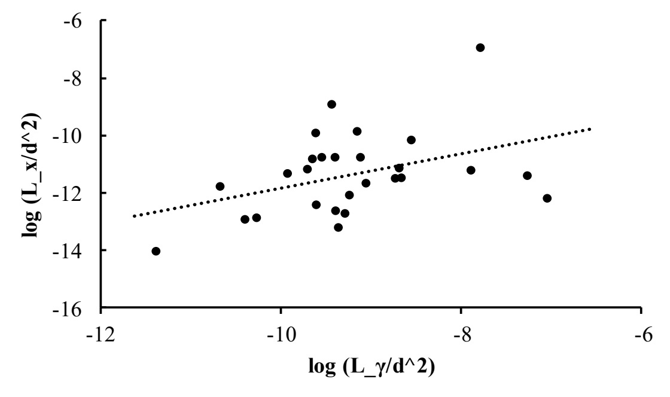


The comparison of calculated and observed luminosities is given in this figure, the line corresponds to the relationship

$$\log L_x = (1.13 \pm 0.09) \log L_{calc} - 3.78 \pm 2.93$$

Taking into account that values of γ_b and γ_p in different pulsars can differ the agreement between L_{calc} and L_x must be recognized as very good, and the used synchrotron model as adequately describing the data of observations.





To compare L_x and L_γ we used data from the 2FGL catalogue of Abdo et al. (ApJS, 208, 17, 2013). This figure shows that indeed there is the correlation between L_x and L_γ, also there is the same tendency for L_x/d^2 vs L_γ/d^2 :

$$\log L_x = (1.22 \pm 0.21) \log L_\gamma - 9.67 \pm 7.18$$

Conclusions

- As was expected there was a correlation between X-ray luminosities of radio pulsars and the rates of losses of their rotational energy. The last one is believed as the main source of energy for all processes in the pulsar magnetosphere. Such a correlation is well known and has been obtained in many previous works for different samples. The last one is given by Prinz & Becker (2015) (see also the references therein).
- The obtained results lead to the conclusion that the division of X-ray loud pulsars into 5 groups proposed by Possenti et al. (2002) is not necessary. As we believe, in fact there are two populations. The first one includes pulsars with long spin periods and weak or absent X-ray radiation. They can emit thermal radiation from the surface. The second population contains objects with rather short periods. They are characterized by high magnetic fields near the light cylinder. This leads to the switching on the synchrotron mechanism and generation of non-thermal X-ray emission. The inverse Compton scattering of soft X-ray quanta on relativistic electrons can explain gamma-ray emission up to energies of hundreds GeV and may be even TeVs (see, for example, Bogovalov (SvAL, 16, 362, 1990)).
- We can conclude that for a purposeful search for new pulsars in hard diapasons we must use radio pulsars with high values of losses of rotational energy and high magnetic fields at the light cylinder.