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Comparison of parameters in pulsars with short and long periods

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The principle-components method is used to analyze the distributions of known radio pulsars in spaces of eigenvectors of correlation matrices for various samples of pulsars and classification parameters (from 4 to 11 parameters characterizing the physical and kinematic properties of the objects). Pulsars with periods $P < 0.1$ s form a separate cluster, far from the cluster formed by "normal" pulsars with $P \sim 1$ s, in all the studied spaces. The spatial velocities of short-period pulsars (106 km/s) are appreciably lower than those displayed by long-period pulsars (334 km/s). The distributions of the pulsars at southern ($Z < 0$) and northern ($Z > 0$) Galactic latitudes do not differ; i.e., there is no anisotropy in the motions in these two directions perpendicular to the Galactic plane, or in the corresponding distributions of the pulsar parameters. A comparative analysis of various parameters of pulsars with short ($P < 0.1$ s) and long ($P > 0.1$ s) periods is carried out. A dependence of the X-ray and gamma-ray luminosities on the magnetic field at the light cylinder is found. This result provides evidence for the formation of hard, non-thermal emission at the periphery of the magnetosphere by the synchrotron mechanism. The dependence of the pulse width on the pulsar period is steeper for pulsars with short periods than for those with long periods. The results obtained support earlier assertions that there are differences in the processes generating the emission in pulsars with $P < 0.1$ s and those with $P > 0.1$ s.

Keywords: Pulsars, classification, clusters

Using the method of principal components we have shown [1–2] that two clusters of pulsars can be distinguished in phase spaces constructed for various parameters of pulsars from the catalog [3]. We exclude from the consideration pulsars in binary systems and globular clusters because their characteristics can be influenced by interactions with other surrounding objects. For example Fig. 1 shows projections in space of three eigenvectors calculated using four parameters (P, dP/dt, W_{10} and Z):

$$\begin{aligned} F_1 &= 0.56 \log P - 0.32 \log \left(\tfrac{dP}{dt}\right) + 0.61 \log W_{10} + \log Z, \\ F_2 &= -0.15 \log P - 0.55 \log \left(\tfrac{dP}{dt}\right) - 0.38 \log W_{10} + \log Z, \\ F_3 &= 0.14 \log P + 2.47 \log \left(\tfrac{dP}{dt}\right) + 0.66 \log W_{10} + \log Z. \end{aligned} \quad (1)$$

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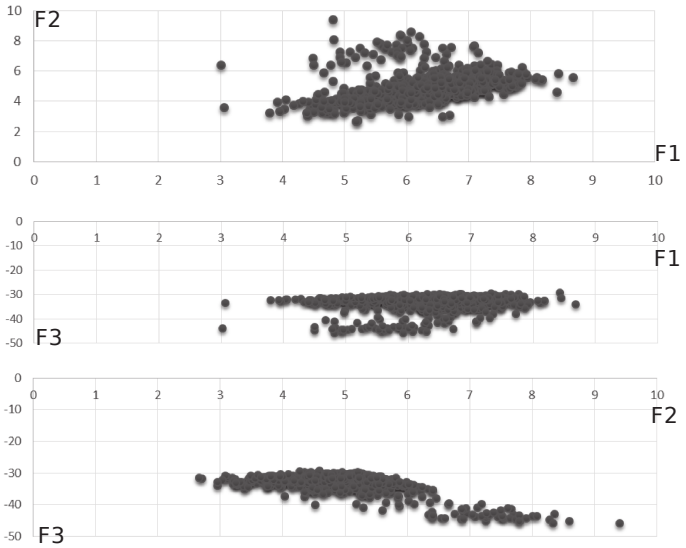


Figure 1 Projections of the pulsar distribution on three planes.

In (1) P is a pulsar period, dP/dt is derivative, W_{10} width of its pulse at the 10% level and Z its distance to the Galactic plane. The separate analysis shows that distributions of pulsars for $Z > 0$ and $Z < 0$ are identical.

Using other parameters (flux density S_{1400}, rates of the rotation energy losses dE/dt, magnetic fields at the surface B_s and at the light cylinder B_{lc} and some others) we obtain the same result – two clusters of pulsars can be distinguished in any phase spaces. The main classifying parameter for these clusters is their period. One of them

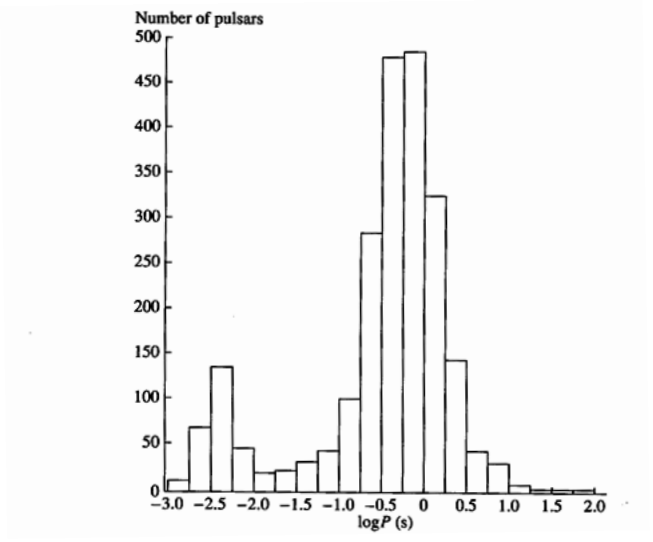


Figure 2 Distribution of pulsar periods.

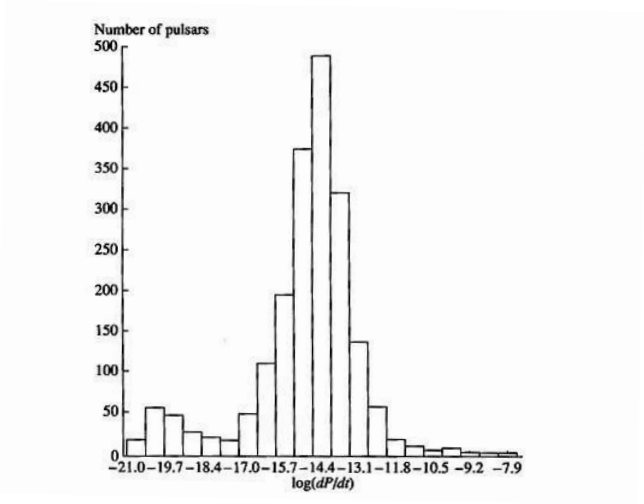


Figure 3 Distribution of derivatives of pulsar period.

is characterized by the short periods ($P < 0.1$ sec), another by $P > 0.1$ sec.

It was detected that space velocities V_{tr} of these two groups differ. The mean values for pulsars with $P > 0.1$ sec $\langle V_{tr} \rangle = 334$ km/sec, for objects with $P < 0.1$ sec $\langle V_{tr} \rangle = 106$ km/sec.

It is well known that distributions of pulsars' periods and their derivatives are bimodal (Figs. 2–3). It means that pulsars with periods of order of tens milliseconds will never become "normal" (with periods $P \sim 1$ sec). Indeed, for a pulsar with $P = 10$ msec and $dP/dt = 10^{-19}$ the time required to acquire a period of 1 sec is 300 billion years exceeding the age of the Universe.

There is no correlation between radio L_r and gamma L_γ luminosities of pulsars considered and their magnetic fields at the surface B_s but the correlation between their X-ray luminosities L_x and B_s is detected [4]. Such a correlation can be explained by heating the surface due to inverse positron flows. As for the absence of dependences $L_r(B_s)$ and $L_\gamma(B_s)$ this is connected with the absence of the dependence of power of curvature radiation on magnetic field:

$$p_{cr} = \frac{2e^2 c\gamma^4}{3\rho^2}. \tag{2}$$

Here e is the charge of electron, γ its Lorentz-factor, c speed of light, ρ radius of curvature of the field line. The power p_{cr} does not depend on B, but on the curvature of field lines only.

We detected the correlations between X-ray and gamma-ray luminosities and magnetic fields at the light cylinder (Figs. 4–5). These correlations provide evidence for the generation of non-thermal hard emission at the periphery of the magnetosphere by the synchrotron mechanism. Indeed for this mechanism the power increases with the growth of magnetic fields.

$$p_s = \frac{2e^4 B^2 \gamma^2 \sin^2 \psi}{3m^2 c^3}, \tag{3}$$

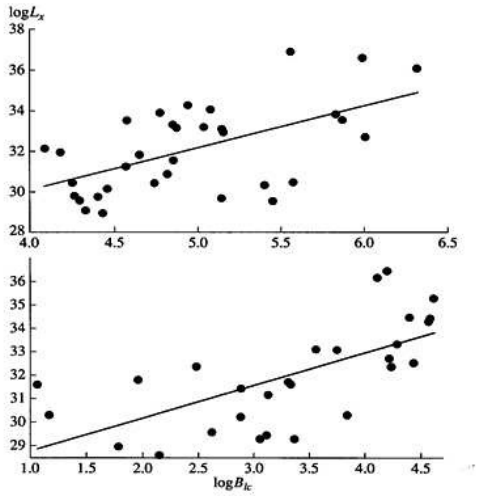


Figure 4 Dependence of X-ray luminosities on magnetic fields at the light cylinder for 33 pulsars with $P < 0.1$ s (upper) and 28 pulsars with $P > 0.1$ s (lower).

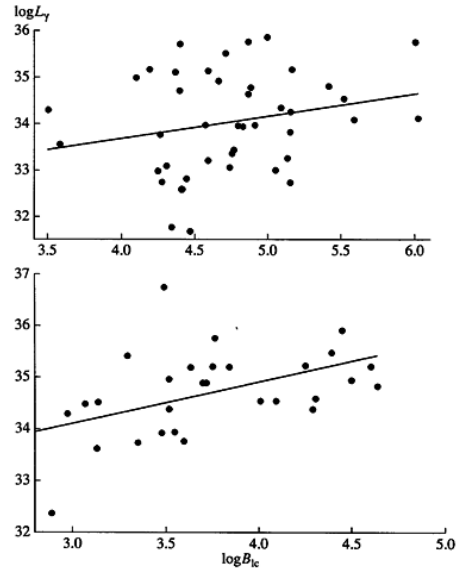


Figure 5 Dependence of gamma-ray luminosities on magnetic fields at the light cylinder for 30 pulsars with $P < 0.1$ s (lower) and 43 pulsars with $P > 0.1$ s (upper).

where ψ is the pitch-angle of relativistic electrons.

The fitted dependences of X-ray and gamma-ray luminosities [5–6] on B_{LC} are:

$$\log L_x = (2.079 \pm 1.088) \log B_{LC} + 21.784 \pm 5.443,$$
$$\text{correlation coefficient is } K = 0.573 \quad (0.0016s \leq P \leq 0.0914s). \tag{4}$$

$$\log L_x = (1.393 \pm 0.643) \log B_{LC} + 27.395 \pm 2.238,$$
$$K = 0.658 \quad (0.1014s \leq P \leq 5.5403s). \tag{5}$$

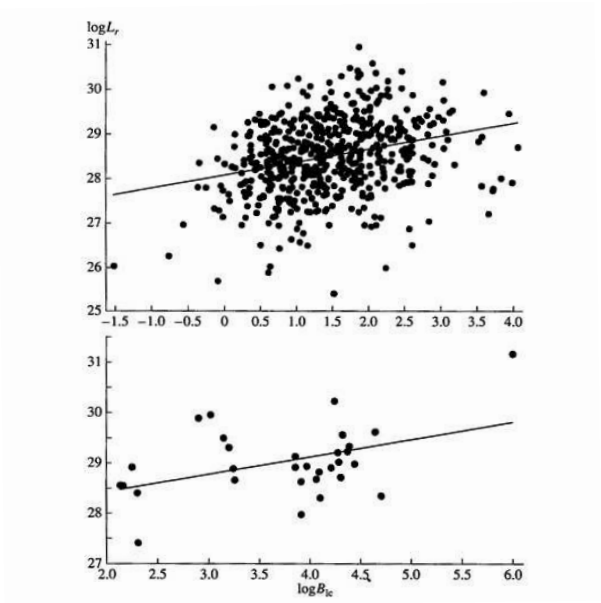


Figure 6 Dependence of radio luminosities on magnetic fields at the light cylinder for 561 pulsars with $P > 0.1$ s (upper) and 31 pulsars with $P < 0.1$ s (lower).

$$\log L_\gamma = (0.488 \pm 0.636) \log B_{LC} + 31.745 \pm 3.023, \quad K = 0.235 \quad (0.0016s \leq P \leq 0.0988s). \tag{6}$$

$$\log L_\gamma = (1.808 \pm 0.527) \log B_{LC} + 31.698 \pm 1.974, \quad K = 0.510 \quad (0.1024s \leq P \leq 0.4137s). \tag{7}$$

Similar correlations are seen in radio range (Fig. 6). Straight lines in this figure are described by the following equations:

$$\log L_r = (0.296 \pm 0.082) \log B_{LC} + 28.100 \pm 0.138, \quad K = 0.287 \quad (0.1014s \leq P \leq 8.5098s). \tag{8}$$

$$\log L_r = (0.345 \pm 0.266) \log B_{LC} + 27.749 \pm 1.024, \quad K = 0.442 \quad (0.0016s \leq P \leq 0.0649s). \tag{9}$$

These equations show that the power of radio radiation in pulsars with short periods depends on magnetic field. Hence the most probable mechanism of this radiation is the synchrotron one.

The weak dependence of L_r on B_{LC} for long period pulsars can be caused by the contribution of objects with $P \geq 0.1$ s and the partial role of the synchrotron mechanism in these objects.

It is of interest to investigate how the luminosity is related to the rate of rotational energy loss:

$$\frac{dE}{dt} = \frac{4\pi^2 I dP/dt}{P^3}. \tag{10}$$

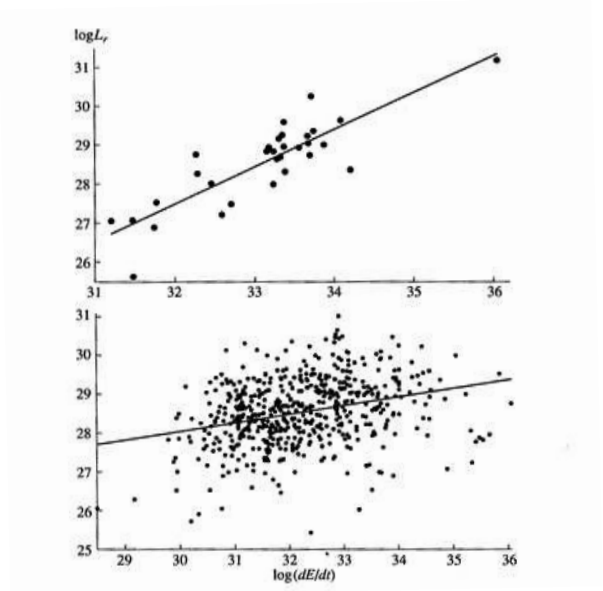


Figure 7 Dependence of the radio luminosity on the rate of rotation energy loss for 31 pulsars with $P < 0.1$ s (upper) and 561 pulsars with $P > 0.1$ s (lower).

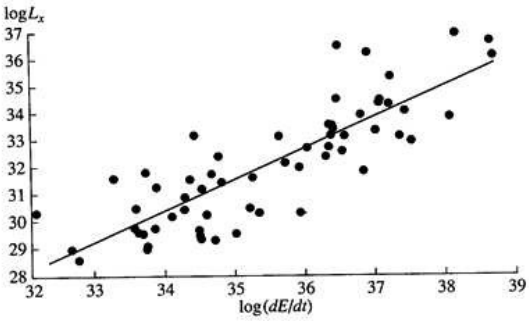


Figure 8 Dependence of the X-ray luminosity on rotation energy loss for 61 pulsars from both groups.

Figures 7–9 show significant correlations between the luminosity and dE/dt, supporting the usual assumption that rotational energy is the basic source of energy for the observed radiation of radio pulsars in all wavebands. Moreover, it follows from these figures that the basic source of energy is the same for pulsars with any periods.

The fitted $L(dE/dt)$ dependences in the three wavebands are

$$\log L_r = (0.948 \pm 0.220)\log(dE/dt) - 2.850 \pm 7.87, \quad K = 0.573 \qquad (0.0016s \le P \le 0.0649s), \tag{11}$$

$$\log L_r = (0.220 \pm 0.058)\log(dE/dt) + 21.439 \pm 1.876, \quad K = 0.300 \qquad (0.1014s \le P \le 8.5099s), \tag{12}$$

$$\log L_x = (1.146 \pm 0.194)\log(dE/dt) - 8.577 \pm 6.898, \quad K = 0.838 \qquad (0.0016s \le P \le 5.5404s), \tag{13}$$

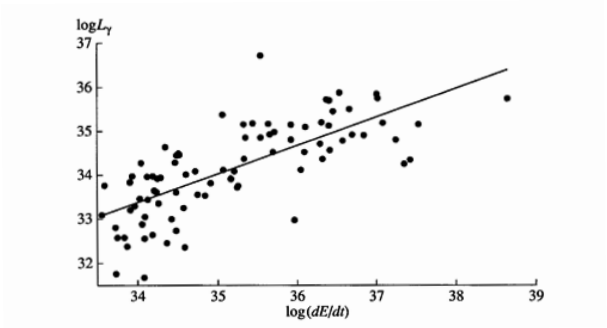


Figure 9 Dependence of the gamma-ray luminosity on rotation energy loss for 86 pulsars from both groups.

$$\begin{aligned} \log L_\gamma &= (0.657 \pm 0.134) \log(dE/dt) + 11.051 \pm 4.727, \\ K &= 0.728 \qquad (0.0016s \leq P \leq 0.4137s). \end{aligned} \tag{14}$$

The dependence of the width of the observed pulses on the period is important for our understanding of the radiation mechanism. Corresponding plots are shown in Fig. 10 for both groups of pulsars. As expected, the tangent of the inclination in the dependence $\log W_{10}(\log P)$ is equal to 0.5 for the main group of pulsars. For a dipolar field, the angular width of the radiation cone is approximately equal to

$$\theta = \left(\frac{2\pi r}{cP}\right)^{1/2}, \tag{15}$$

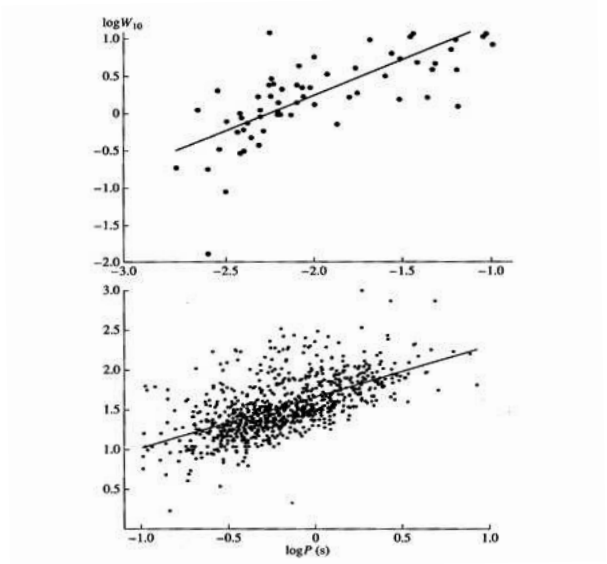


Figure 10 Dependence of the pulse width on the pulsar period for pulsars with $P < 0.1$ s (upper) and $P > 0.1$ s (lower).

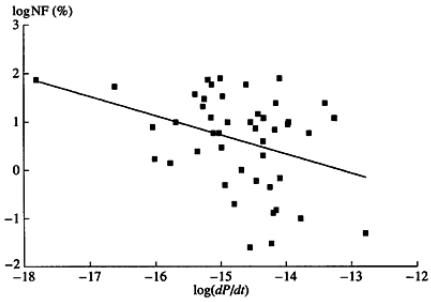


Figure 11 Nulling fraction as a function of the period derivative.

where r is the distance from the center of the neutron star. The width measured in units of time (W_{10} is given in milliseconds in Fig. 10) is equal to θP and is proportional to $P^{1/2}$. The radiation of pulsars with short periods is generated near the light cylinder, where relativistic effects become appreciable. In this case, it is predicted that the profile width (in units of time) should be proportional to the period [7]:

$$W = \frac{AP}{2\pi}(1-\beta^2)^{3/2}, \tag{16}$$

where $\beta = r/r_{LC}$, $A^2 = 2^{1/(2+\alpha)} - 1$ and α is the spectral index of the pulsar radiation.

The corresponding equations for $W_{10}(P)$ [3] have the form

$$\begin{gathered}\log W_{10} = (0.960 \pm +0.196)\log P + 2.203 \pm 0.396, \\ K = 0.764 \quad \text{for} \quad 69 \quad \text{objects} \quad \text{with} \quad 0.0016 \le P \le 0.0962s,\end{gathered} \tag{17}$$

$$\begin{gathered}\log W_{10} = (0.638 \pm 0.056)\log P + 1.666 \pm 0.021, \\ K = 0.607 \quad \text{for} \quad 854 \quad \text{objects} \quad \text{with} \quad 0.1014 \le P \le 8.5098s.\end{gathered} \tag{18}$$

Silent periods – the sudden disappearance of pulses followed by their re-appearance are observed in the radio emission of some pulsars. The nature of this effect, which is called "nulling", remains unknown. The most complete list of pulsars with nullings contained in [8] shows that there is no correlation between the rate of occurrence of nullings (nulling factors, NF) and pulsar periods. We detected the dependence $NF(dP/dt)$ (Fig. 11). It means that the greater the power injected into the pulsar magnetosphere (10) the more stable its radiation (the smaller the NF).

It was shown in [8] that nullings were observed in pulsars with $P > 0.2$ s only and mode switchings took place in some pulsars with detected nullings. These two effects may be closely related. It is worth noting that mode switchings are observed in pulsars with $P > 1$ s only. One possible origin of nullings and mode switchings could be the modification of the distribution function of the electrons in the primary beam and the secondary electron-positron plasma [9].

The degrees of linear and circular polarization [10] are higher in pulsars with $P < 0.1$ s than in those with $P > 0.1$ s. The corresponding values are $\langle L_l \rangle = 59.41\%$ and 33.08%, $\langle L_c \rangle = 20\%$ and 13.7%. Both results testify to an additional mechanism influencing the polarized radiation in the outer layers of the magnetosphere.

Conclusion

The results obtained in this study testify to systematic differences in the parameters of pulsars with $P < 0.1$ s and with $P > 0.1$ s. This supports the earlier suggestion that the regions of the magnetosphere in which the observed radio emission is generated and the mechanisms responsible for this radiation are different in these two groups. We believe that the main mechanism operating in pulsars with $P > 0.1$ s is curvature radiation and the synchrotron radiation is the main mechanism in pulsars with $P < 0.1$ s. It works near the light cylinder of these objects.

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