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Pulsar statistics and two types of pulsars

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Summary. Under the configuration of new pulsar spindown ($\dot{P} \propto P^2$) we proposed recently, some pulsar statistics are reinvestigated. The results are interesting. First, the distribution of pulsar periods can be explained naturally. Second, there might be two types of pulsars which could be correlated with two types of supernova. Third, the magnetic decay probably exists.

Key words: pulsars – pulsar statistics – supernova – magnetic decay

I. Introduction

The distribution of pusar periods is characterized by its rapid decrease in number for $P > 1$ s, P being the pulsar period. Taylor and Manchester (1977) have shown that the selection effects on the distribution are small which means it closely approximates the true distribution. Another characteristic is there are two maxima at $P \sim 0.5$ s and $P \sim 1.25$ s with an appreciable dip around $P \sim 1$ s.

The authors have proposed two emission mechanisms for pulsars recently – the neutrino cyclotron radiation (Peng et al., 1982) and the magnetic dipole radiation (Huang et al., 1982) from superfluid vortexes in neutron stars. We have shown that these two radiations respectively provide a new mechanism for pulsar spindown, in which the spindown rate is proportional to the square of the period ($\dot{P} \propto P^2$). This spindown mechanism is dominant when $P > 1$ s. We will show in this paper that the distribution of the pulsar periods could be explained naturally if this new mechanism is considered. Based on this interpretation, we propose that the magnetic decay is preferable and there may exist two types of pulsars.

II. On the characteristic age

The age of an individual pulsar is usually estimated from

$$\tau = P/2\dot{P}, \tag{1}$$

where $\dot{P}$ is the period derivative. The characteristic ages calculated in this way for the two pulsars – Crab and Vela pulsars, which are identified with supernova remnants, agree reasonably well with the ages of these remnants. For all other pulsars, however, it is just an inference to take the characteristic age as true age of a pulsar.

As pointed out by Arnett and Lerche (1981), however, that if the pulsar changes its dominant radiation mode during its evolution, then the relevance of the characteristic age to the true age is suspect.

Considering the new mechanism for pulsar spindown proposed in our first two papers, we can show that the characteristic age may not be an accurate indicator of a pulsar's true age, and even of its rate of aging as well. For simplicity, when $P > 1$ s we consider only a $\dot{P} \propto P^2$ spindown mechanism:

$$\dot{P} = BP^2, \tag{2}$$

then, obviously we have

$$\tau = P^{-1}/2B,$$

$$P \propto (\mathrm{const} - Bt)^{-1}$$

and

$$\tau \propto (\mathrm{const} - Bt). \tag{3}$$

When $t \to t_\infty = \mathrm{const}/B$, the lifetime of the pulsars, we have

$$P \to \infty \tag{4}$$

and

$$\tau \to 0. \tag{5}$$

On the contrary, considering only a spindown mechanism going as $\dot{P} \propto P^{-1}$ when $P < 1$ s, we have (Kundt, 1981)

$$\frac{\tau}{\tau_0} = e^{t/\tau_D}(1 + (\tau_D/\tau_0)(1 - e^{-t/\tau_D})), \tag{6}$$

$$\frac{P}{P_0} = (1 + (\tau_D/\tau_0)(1 - e^{-t/\tau_D}))^{1/2}, \tag{7}$$

where P_0, τ_0 and τ_D are initial period, initial braking time and the characteristic decay time, respectively. So P and τ increase with t. We conclude, therefore, that in this case τ is no longer a monotonic variable during the course of pulsar evolution. It first increases with t, then decreases after reaching some maximum of τ, $\tau_{\max}$, which is dependent on the parameters entering the two spindown mechanisms.

Figure 1 is just a typical example of such a case. The dots in the diagram show an observational distribution, $(P\dot{P})^{1/2}$ vs τ, for 269 pulsars, and the dotted line is a theoretical evolutionary track for a model of $\dot{P} = A\exp(-\xi t)P^{-1} + BP^2$, implying that different radiation mechanisms ($\dot{P} \propto P^{-1}$, $\dot{P} \propto P^2$) are at work. The parameters in Fig. 1 are $A = 5\,10^{-14}$, $B = 5\,10^{-16}$, the characteristic decay time scale $(1/\xi) = 5\,10^5$, and $P_0 = 0.001$.

An interesting phenomen is that no pulsar is known with $\tau > 3\,10^9$ yr (Kundt, 1981). It could possibly be an indication of the

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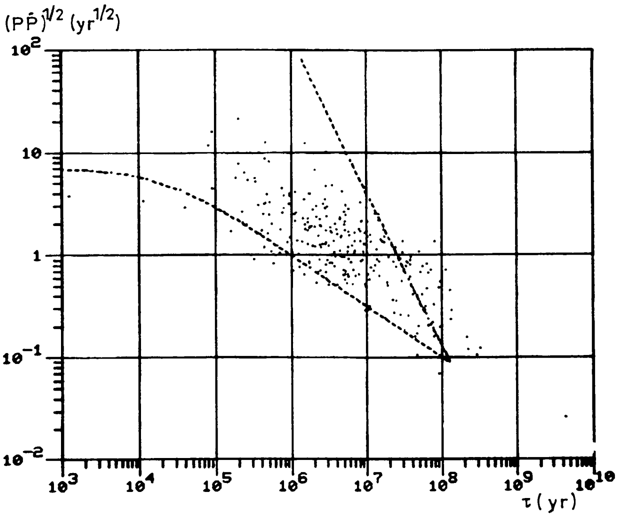

Fig. 1. Relation between quantity $(P\dot{P})^{1/2}$ and "characteristic age" $\tau = P/2\dot{P}$ for 269 pulsars; the dotted lines correspond to the relations expected for the mechanisms described in the text

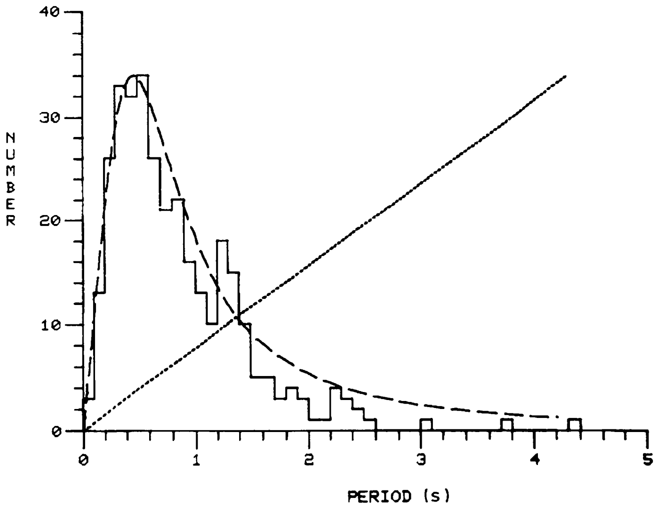

Fig. 3. Histogram of pulsar periods, compared with the predictions of a $\dot{P} \propto P^{-1}$ model (dotted line) and of our model (dashed line), for the case of no magnetic decay

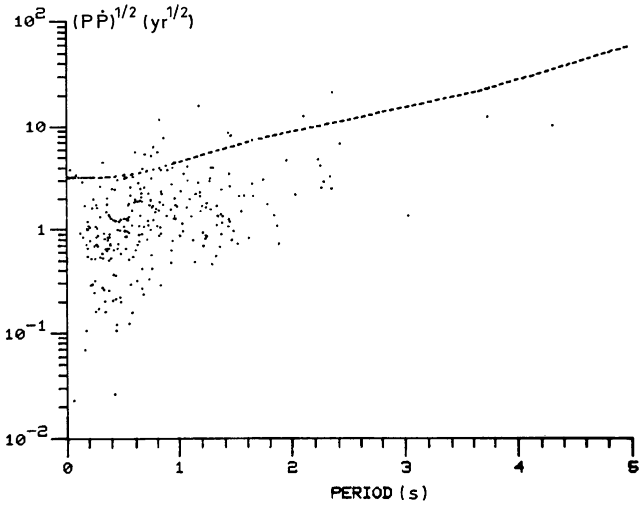

Fig. 2. Relation between $(P\dot{P})^{1/2}$ and the period P. The dotted line corresponds to relation (8)

existence of two different spindown mechanisms in view of our analyses described above, and it could also show that τ might not be a good statistical quantity. As a result, it may not be appropriate to study the τ-distribution of pulsars.

Now we consider the relation $(P\dot{P})^{1/2}$ vs P instead of τ, since P is an indicator of the pulsar rate of aging. We have

$$(P\dot{P})^{1/2} = (Ae^{-\xi t} + BP^3)^{1/2}. \tag{8}$$

When $P < 0.5$ s, the P^2 spindown mechanism does not work. We have

$$(P\dot{P})^{1/2} = (Ae^{-\xi t})^{1/2}, \tag{9}$$

$P\dot{P}$ is related to the magnetic field through the parameter A, but does not correlate with P, as can be obviously seen in Fig. 2. When $P > 1.25$ s, the P^2 spindown mechanism does work, so we have

$$(P\dot{P})^{1/2} = (BP^3)^{1/2}, \tag{10}$$

where B is a parameter relating to the internal structure of the pulsar, or we have

$$\log(P\dot{P})^{1/2} = a + 1.5 \log P. \tag{11}$$

If we take the regression equation $\log(P\dot{P})^{1/2} = a + b \log P$, a simple statistical study of the relation between $\log(P\dot{P})^{1/2}$ and $\log P$ over the region $P > 1.25$ s shows that the regression coeficient b is equal to 1.540, and the standard deviation of b is 0.378.

This result is very interesting. First, it shows that $(P\dot{P})^{1/2}$ is not always a quantity related to the surface magnetic field strength, especially for $P > 1$ s. Second, it does not contradict the P^2 spindown mechanism.

III. On the distribution of pulsar periods

As we pointed out above, the distribution of the pulsar periods is characterized by the presence of two maxima at $P \sim 0.5$ s and 1.25 s. Some authors have tried to interpret these features by introducing two types of pulsars with different initial periods (see e.g., Mnatsakanyan, 1979).

According to our model, the effects of the new spindown mechanism ($\dot{P} \propto P^2$) will be dominant when the pulsar periods $P > 1$ s, and the probability to find a pulsar with $P > 1$ s is relatively small due to its inverse proportionality to $\dot{P}$. Neglecting the small selection effects on the distribution, we can express the differential number of pulsars expected in an interval of periods P to $P + dP$ at time t as

$$\frac{dN}{dP} = C\frac{R}{\dot{P}} = C\frac{R}{Ae^{-\xi t}p^{-1} + BP^2}, \tag{12}$$

where R is the rate of creation. A and B are the parameters in the two spindown mechanisms ($P \propto P^{-1}$, and $\dot{P} \propto P^2$). As usual, in deriving Eq. (12) we have implicitly assumed that pulsars are produced at a constant rate, and that all the other parameters involved in the constant C are the same for all pulsars. We obtain the theoretical distribution for two different cases, which correspond to no magnetic decay, $\xi = 1.0\,10^{-10}$, and to the existence of magnetic decay, $\xi = 1.0\,10^{-7}$, respectively. For all other parameters we take the same values in both cases: $R = 40$, $P_0 = 0.002$ s, A

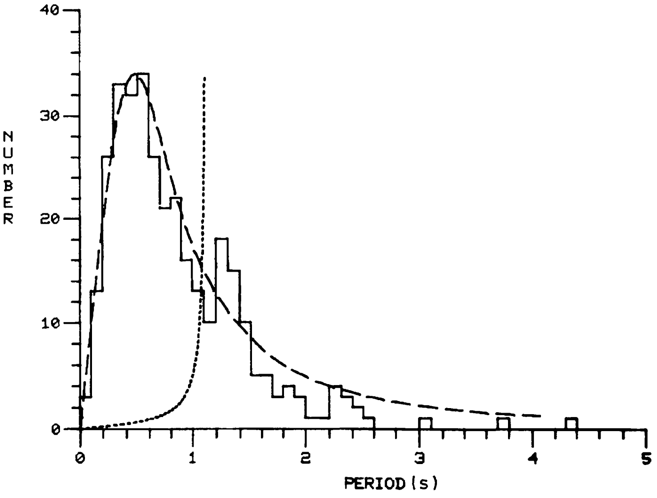

Fig. 4. Same as Fig. 3, but with magnetic decay

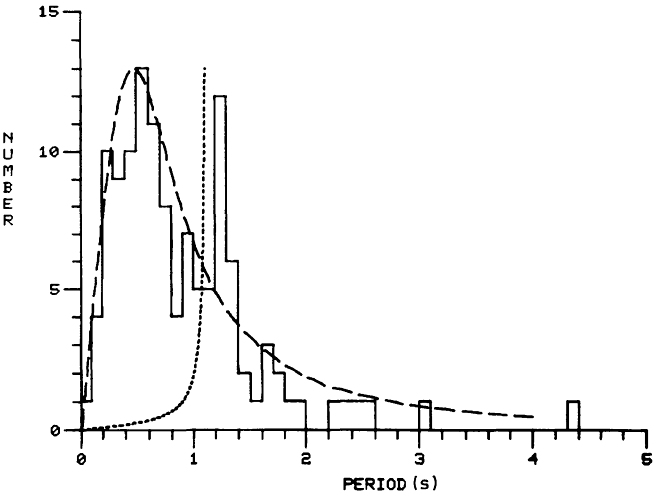

Fig. 5. Same as Fig. 3, but the histogram now refers to pulsars with distances $D \leqq 1.5$ kpc

$=2.0\,10^{-15}$ and $B=1.0\,10^{-14}$. The results are given in Figs. 3 and 4, respectively.

The histograms in these two diagrams show the observational distributions; the dotted lines illustrate the theoretical ones derived from the $\dot{P} \propto P^{-1}$ model only, and the dashed lines represent the theoretical ones from the $\dot{P}=A\exp(-\xi t)P^{-1}+BP^2$ model. Obviously, we cannot interpret the observational distribution through the $\dot{P} \propto P^{-1}$ spindown mechanism only, no matter whether magnetic decay exists or not. Generally, however, we can fit the observational distribution through model $\dot{P}=A\exp(-\xi t)P^{-1}+BP^2$ with or without magnetic decay. The model without magnetic decay is a little bit better than that with magnetic decay, but the differences are very small.

The only question is that the second maximum at $P \sim 1.25$ s cannot fit with this model. Now if we look at the situation in Fig. 4 further, in the vicinity of $P \sim 1.1$ s the dotted line has a maximum, which reflects the fact that a maximum period exists in the magnetic decay model, i.e. $\dot{P}$ is very small, and P is almost constant with t. From this, we infer that there might be two types of pulsars. The majority of the pulsars belong to Type I which could be depicted with the $\dot{P}=A\exp(-\xi t)P^{-1}+BP^2$ model, and a minority belongs to Type II which could be represented with the model $\dot{P}=A\exp(-\xi t)P^{-1}$ and $1.0\,10^{-8}<\xi<1.0\,10^{-7}$. A superposition of the distributions of these two types of pulsars corresponds to the observational one.

Table 1. Candidates for Type II pulsars

PSR	P (s)	$\dot{P}$ $(10^{-15}\,\mathrm{s\,s^{-1}})$	L_r $(\mathrm{erg\,s^{-1}})$
0011+47	1.2407	0.59	
0138+59	1.2229	0.378	
0301+19	1.3876	1.2942	$3.8\,10^{26}$
0809+74	1.2922	0.16	$1.4\,10^{26}$
0844−35	1.1161	1.57	
0853−33	1.2675	1.677	$3.4\,10^{25}$
0909−72	1.3629	0.333	$6.8\,10^{26}$
1237+25	1.3824	0.956	$1.2\,10^{26}$
1530−53	1.3689	1.428	$9.8\,10^{26}$
1612+07	1.2068	2.346	$2.9\,10^{26}$
1700−32	1.2118	0.7	$4.3\,10^{26}$
1701−76	1.1910	1.88	$1.1\,10^{26}$
1745−56	1.3323	2.12	$8.1\,10^{26}$
1919+21	1.3373	1.3479	$2.2\,10^{26}$
2044+15	1.1383	0.2	$6.3\,10^{26}$

Physically speaking, the Type I pulsars might be born with rather large radii (say, about 20 km), which means a relatively low central density and stiff equation of state in the interior of pulsars. In that case, the radius of the $^3P_2$ superfluid region is rather large and the effects of the magnetic dipole radiation from superfluid neutrons on pulsar evolution are significant. The general features in the distribution then could be interpreted as Type I pulsars. On the contrary, the Type II pulsars have rather small radii (say, less than 10 km), which implies a relatively high central density and a soft equation of state in the interior. The $^3P_2$ superfluid regions in the interior of Type II pulsars, therefore, are very small, and the effects of the P^2 spindown mechanism on pulsar evolution are insignificant indeed. It seems then that only one mechanism, $\dot{P}=A\exp(-\xi t)P^{-1}$, is effective in Type II pulsars, and the second maximum near $P \approx 1.25$ s in the distribution could be explained with Type II pulsars of some characteristic decay time scale $(1/\xi)$.

The small number of Type II pulsars may be only an apparent phenomenon due to the very low luminosities for pulsars with $P \approx P_{\max}$. In fact, in Fig. 5 the features of the histogram showing a distribution for pulsars of distances $D \leqq 1.5$ kpc support this idea. The second maximum near $P \sim 1.25$ s in Fig. 5 is more striking than that in Figs. 3 and 4. This is an evidence that the pulsars round $P \approx 1.25$ s in Figs. 3 and 4 are mainly nearby ones of low luminosities.

Besides, we would like to point out that the period $P \approx 1.25$ s of the second maximum where Type II pulsars dominate is quite consistent with the transition period $P=1.25$ s above which the new spindown mechanism $(\dot{P} \propto P^2)$ is dominant as we have shown in our previous papers, and this consistency might be in favour of the existence of two types of pulsars.

Here we propose a rough approach to defining the Type II pulsars round $p \approx 1.25$ s. According to our definition, only the magnetic dipole radiation is efficient for Type II pulsars, so the values of $(P\dot{P})$ are relevant to the surface magnetic field strengths of pulsars. The weak luminosities then are corresponding to small values of $(P\dot{P})$. As a result, a low radio luminosity and a small value of $(P\dot{P})$ can be used as criteria for defining Type II pulsars with $P \approx 1.25$ s.

The question now is how to choose these critical values. Actually, the basic question here lies on whether there are any connections between these two types of pulsars and two types of supernova. If the two types of pulsars described above exist, they might be correlated with two types of supernova in the way as follows: the explosion of Type I supernova is rather mild which could lead to remnants with relatively low central densities and relatively large radii, i.e. Type I pulsars. Conversely, the rather violent explosion of Type II supernova may lead to remnants with relatively high central densities and relatively small radii, i.e. Type II pulsars. Obviously, the critical values for defining Type II pulsars cannot be obtained just from such a simple consideration, and can only be given somewhat arbitrarily: $L_c = 1.0\,10^{27}$, $(P\dot{P})_c = 4\,10^{-15}$. Several candidates for Type II pulsars round $P \sim 1.25$ s are listed in Table 1.

As for pulsars with $P < 1$ s, it is hard to say to which type they belong. But most of pulsars with $P > 1.3$ s may belong to Type I, and in that case the values of $(P\dot{P})$ are not relevant to the magnetic field strength.

In conclusion, although the approach for defining Type II pulsars is apparently obscure, the facts from which we propose that two types of pulsars might exist could well be true. More researches on the two types of supernova would shed light on this problem.

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