TWO TYPES OF PULSARS

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ABSTRACT. To sort out the whole sample of pulsars with measured P and $\dot{P}$ into two types has much something to do with the origin and evolution of neutron stars. Under the configuration of two types of pulsars with different spindown mechanism, we have discussed a variety of their properties, including their radio emission mechanism, space velocities, interior structures and evolutionary modes. The fact that different type of pulsars does have quite different properties indicates that the processes to create neutron stars may have two distinct types, say, Type II supernova explosion and the collapse of accreting white dwarfs. The evolutionary mode for our Type I pulsars provides such a key link between binary pulsars and X-ray binary pulsars that we may propose a self-consistent scenario for binary pulsars, X-ray binary pulsars, fast pulsars as well as Type I pulsars.

1. INTRODUCTION

The idea of ' Two Types of pulsars ' is not a new one proposed recently. Till now, at least four different kind of arguments have appeared.

The first one came out in 1977, when Helfand and Tademaru suggested that there may have two types of pulsars with different space velocities, scale heights and the initial field strengths, Class A and Class B (Helfand and Tademaru, 1977), based on their analyses of pulsars' proper motion and $|Z|$ distribution. They also postulated that Class A sources may originate in tight binaries where their impulse acceleration at birth is insufficient to remove them from the system, while Class B sources may arise from single stars or loosely bound binaries and are accelerated to high velocities by their asymmetric radiation pressure. Obviously, this is a very suggestive idea, especially for the origin of neutron stars. Thereafter, Radhakrishnan (1984) further advanced some arguments to show that pulsar velocities are determined by their binary histories and not governed in any way by their magnetic fields.

Also in 1977, Manchester and Lyne (1977) proposed that there may exist two types of pulsars with different beaming mechanism in order to explain the behavior of interpulse in some pulsars, one forming a coni-

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cal beam directed outward along the open field lines and the other forming a beam directed approximately perpendicular to the magnetic axis.

In the IAU Symposium held in Bonn in 1981, this idea got ahead. As pointed out by Radhakrishnan (1981) in his concluding review, that the very young and very old pulsars may function in a different way. Since then, this concept has been expounded further mainly by Soviet astronomers, Malov and his collaborators. They suggested (Malov, 1985) that the radio emission from short period pulsars could be described by the light cylinder model and that from long period pulsars conforms to the polar cap model, mainly based on the distinct relation between pulse width and period.

The problem here is that we need to clarify the relation between the pulse width and the angular width of the radiation cone as pointed out by Prószyński (1979).

In 1982, Alpar and his collaborators (1982) considered that the millisecond pulsars and some pulsars with short periods, long spindown ages as well as a few binary pulsars may constitute a new type of pulsars with accretion spun-up histories.

There were several talks given in this conference (see, e.g. van den Heuvel) about the millisecond pulsar formation and evolution. They all suggest an evolutionary scenario for binary pulsars that the spin-up by accretion moves the pulsars back from the ' graveyard ' into the region of ' living ' pulsars along the horizontal tracks in the B_S vs P diagram (see, e.g. van den Heuvel, 1984, Fig. 2). Surely, this evolutionary stage should have something to do with the X-ray binary pulsars. However, some very large periods for X-ray binary pulsars (> 1000. second) are incompatible with the evolutionary tracks from the standard magnetic decay model in which the tracks in the diagram of log B_S vs log P become nearly vertical in the end, caused by the magnetic field decay when their age exceeds the decay time scale. It means that the pulsars stayed in the ' graveyard ' will evolve furhter but almost with the same periods as they had at the time of entering the ' graveyard ', according to the magnetic decay model. And these periods would be less than 1000. sec.

We will show briefly in section 3 that this problem could be overcome, all the binary pulsars, X-ray binary pulsars and millisecond pulsars would find their right places in our proposed evolutionary scenario for Type I pulsars.

In 1983, my collaborators and I proposed that there may exist two types of pulsars with different spindown mechanism (Huang et al, 1983). Now we find that this idea may be very useful for studying the origin of neutron stars. The emphasis of my talk will be put on it.

2. TWO TYPES OF PULSARS WITH DIFFERENT SPIN DOWN MECHANISM

2.1. New Spin Down Mechanism ($\dot{P} \propto P^2$)

As we have shown (Huang et al, 1982) that there is a net magnetic moment for neutron pairs coupled by the $^3P_2$ wave interaction. Thus, there should exist an electromagnetic interaction between $^3P_2$ superfluid neutrons and the internal magnetic field, leading to dipole radiation. The $^3P_2$ superfluid neutrons should lose energy by this radiation, and the total power of it , W_m , is proportional to the total number of superfluid vortexes, which is proportional to the angular velocity of pulsar, Ω , or

$$W_m = C\,P^{-1}$$

here C is a coefficient relating to the interior structure of neutron stars, P the period of pulsars. Because of the heavy absorption in the interior of neutron stars, not a bit of such emission could come out of the surface of neutron stars. And it is easy to see that the resulting period derivative is proportional to P squared

$$\dot{P} = B\,P^2$$

So, generally the spindown rate of pulsars should have a form as follows

$$\dot{P} = A\,e^{-2t/\tau_D}\,P^{-1} + B\,P^2$$

τ_D here is the decay time scale. The first term on the right-hand side is just one accepted generally, and the coefficient B is constant with time, which implies that the internal magnetic field is constant.

The statistical analysis shows that the relation between lg $\dot{P}$ and lg P changes from an inverse proportionality to a direct one as pulsars evolve (Peng et al, 1982). For $P < 0.5$ sec and $P > 1.25$ sec, this relation is significantly different which is just what was suggested from our model. And the two characteristic periods, 0.5 sec and 1.25 sec, here have their physical implication as we'll show below.

2.2. Two Types of Pulsars with Different Interior Structures

The distribution of pulsar periods is characterized by the presence of two maxima at about 0.5 sec and 1.25 sec,see Fig.1. The selection effect caused by the instrumental bias against the detection of short period pulsars may affect the distribution only at short period end (Lyne et al, 1985), but will not change the positions of the two maxima.

Fig.2 shows a distribution of periods for pulsars with distances D $\leqq$ 1.5 kpc. The features in this distribution are similar to that for the whole sample of pulsars except

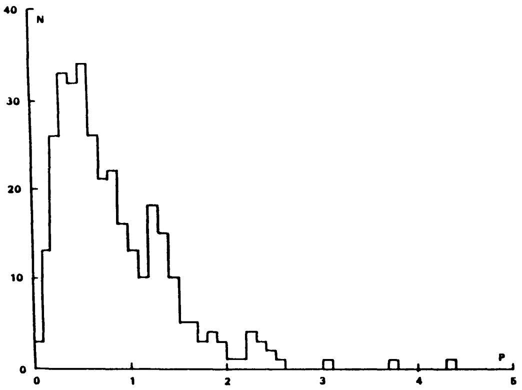

Fig. 1. Histogram of pulsar periods, showing the two maxima at 0.5 sec and 1.25 sec

that the second maximum near 1.25 sec is more striking.

This difference simply shows that the pulsars round 1.25 sec are mainly nearby ones with low luminosity. This conjecture can be confirmed from the luminosity distribution. Fig.3a illustrates the luminosity distribution for the whole sample of pulsars, and that for pulsars within 1.5 kpc of the sun is indicated in Fig.3b.

As you can see that the low luminosity pulsars dominate in Fig.3b. The broken line histogram in this diagram shows the distribution for pulsars with P > 1.2 sec and < 1.4 sec, which again indicates that pulsars round 1.25 sec are mainly that with low luminosity.

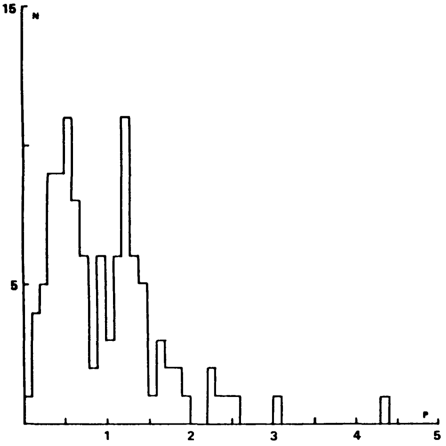

Fig. 2. Same as Fig. 1, but the histogram is for pulsars with $D \leqq 1.5$kpc

The theoretical distributions to fit these features are shown in Fig. 4. The dotted line illustrates the theoretical one derived from $\dot{P} = A \exp(-2t/\tau_D)\, P^{-1}$ model with the value of $\tau_D \sim 10^7$ yr. And the solid line represents the one from the $\dot{P} = A P^{-1} + B P^2$ model with the value of $B = 5A$, no matter whether magnetic decay exists or not.

From this, we infer that there may have two types of pulsars. Type I pulsars could be depicted with the model of $\dot{P} = A P^{-1} + B P^2$ and $B = 5A$; Type II pulsars can be represented with the model of $\dot{P} = A \exp(-2t/\tau_D)\, P^{-1}$ and $\tau_D \sim 10^7$ yr.

Such a difference in spindown mechanism between Type I and II pulsars suggests a rather large difference in the $^3P_2$ superfluid region between

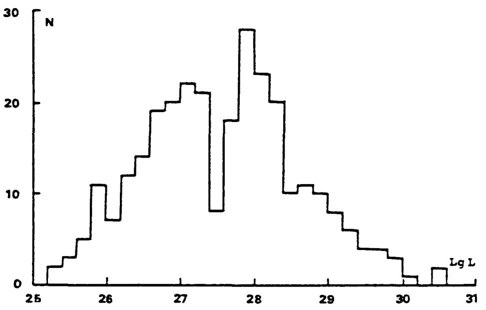

Fig. 3a. Histogram of pulsar luminosity

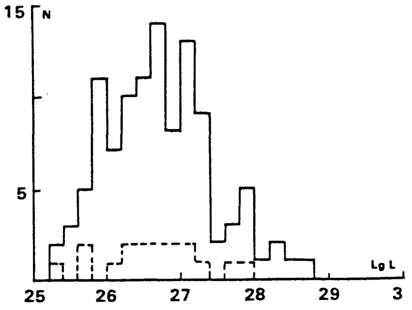

Fig. 3b. Same as Fig. 3b, but the histogram now refers to pulsars with $D \leqq 1.5$kpc, broken line one for $1.2<P<1.4$

these types. That is, the $^3P_2$ superfluid region for Type I pulsars is so large that the effects of new spindown mechanism ($\dot{P} \propto P^2$) on pulsar evolution are significant. On the contrary, the Type II pulsars have very small $^3P_2$ superfluid region, so only one mechanism, $\dot{P} \propto P^{-1}$, is effective on this type of pulsars. When we say, then, that there may exist two types of pulsars with different spindown mechanism, one should realize that it means with different interior structure indeed.

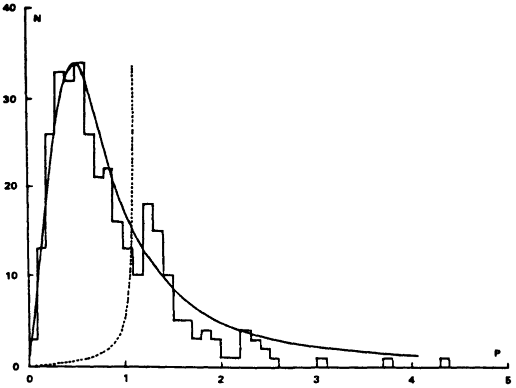

Fig. 4. Histogram of pulsar periods, compared with the prediction of a $\dot{P} \propto P^{-1}$ model (dotted line) and of our model (solid line)

Now the question is how to classify these these two types of pulsars. The criteria to sort out the whole sample of pulsars with measured P and $\dot{P}$ into two types are as follows (Huang et al, 1985).

The first one is a relation that Type II pulsars should obey:

$$\lg P = 2 \lg P_\infty - \lg (P + \tau_D \dot{P})$$

here P_∞ is the maximum period for Type II pulsars. Another one is that the surface magnetic field of two typical pulsars at their birth should follow a relation

$$B_{II} \approx 29 B_I$$

based on the assumptions that the two typical pulsars of each type are different in their interior structure as shown above and that the magnetic fields of the progenitors for these two typical pulsars are the same.

The total number of the resulting sample of Type I pulsars is 130 and that of Type II is 164. The period distribution for Type II pulsars with distances $D \leqq 1.5$ kpc is really typical of the $\dot{P} \propto P^{-1}$ spindown mechanism, represented by the dashed line in Fig. 5. The peak round 0.6 sec in this figure could be produced by the uncertainties in the derivation of pulsars' distances or it just reflects the uncertainties in our Type II sample. In view of the crudeness of our method to distiguish between Type I and II pulsars, however, this histogram still convinces us that our sample of Type II pulsars is basically reliable.

3. BASIC PROPERTIES FOR TWO TYPES OF PULSARS

3.1. Evolutionary Modes for Two Types of Pulsars

Type II pulsars are those typical of $\dot{P} \sim P^{-1}$ spindown mechanism with mag-

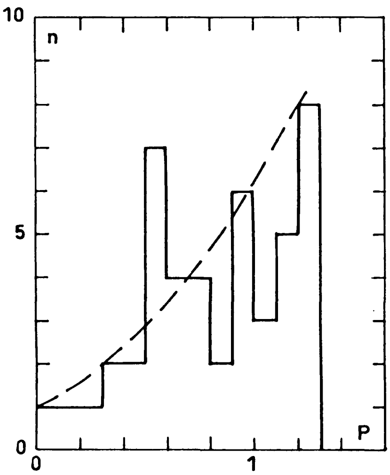

Fig. 5. Period distribution for Type II pulsars with D≦1.5 kpc

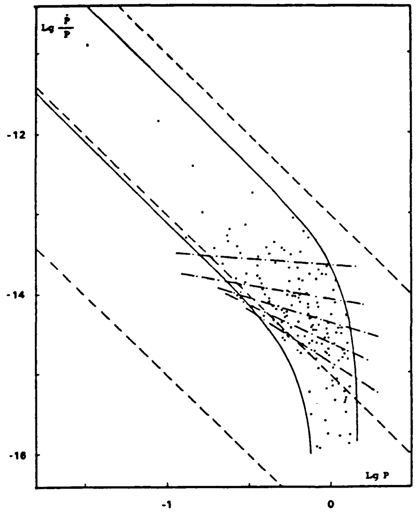

Fig. 6. Distribution for Type II pulsars, showing the magnetic decay

netic decay, suggesting an usual evolutionary mode as can be seen in Fig. 6. The initial magnetic fields for this type of pulsars are distributed over a narrow range, $9.4\text{x}10^{11}$ - $6.6\text{x}10^{12}$ Gauss, consistent with those predicted theoretically by Flowers and Ruderman (1977).

We can also illustrate the evolutionary tracks in another way (Deng et al, 1987), i.e. in a diagram of lg t vs lg P. The true ages for Type II pulsars are given below

$$t = \frac{\tau_D}{2} \ln \left(\frac{2}{\tau_D} \frac{P}{2\dot{P}} + 1 \right)$$

From our considrations (Huang et al, 1987a), the value of decay time scale, , is about 10^7 yr, one obtained by Lyne et al (1985) is about $9\text{x}10^6$ yr, and that by Krishnamohan (1987) is about $2\text{x}10^7$ yr. Taking 10^7 yr, we can get evolutionary tracks for Type II pulsars, represented by dashed lines in Fig. 7. It shows a maximum period of about 1.3 sec.

However, The evolutionary mode for Type I pulsars is totally different from that of Type II. The true ages for Type I pulsars are determined with the following formula

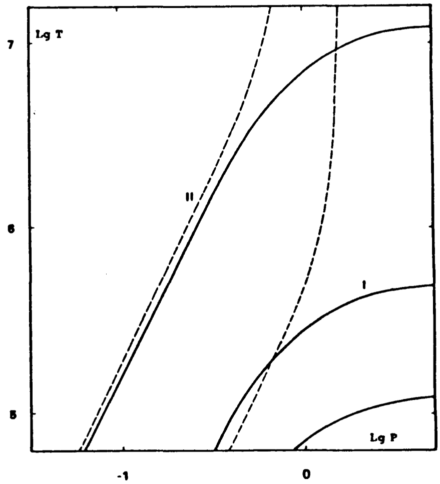

Fig. 7. Evolutionary modes for Type I pulsars (solid lines), and Type II pulsars (dashed lines)

$$t_{II} = \frac{(1+5P^3)}{3\,5^{2/3}P\dot{P}}\left[\frac{1}{2}\ln\left(\frac{5^{2/3}P^2 - 5^{1/3}P + 1}{(5^{1/3}P+1)^2}\right.\right.$$
$$\left.\left. + 3^{\frac{1}{2}}\left(tg^{-1}\frac{2\,5^{1/3}P+1}{3^{\frac{1}{2}}} + \frac{\pi}{6}\right)\right]\right.$$

As you can see from Fig. 7 that the solid lines, the tracks for Type I, go another way, indicating a rapidly growing of periods for Type I pulsars after P > 1 sec. In other words, Type I pulsars will soon die after P is larger than some typical value.

This evolutionary mode does supply a key link between "binary pulsars" and X-ray binary pulsars. The "binary pulsars" here refer to those systems composed of a pulsar with a normal non-degenerate star as a companion, but they are not expected to be observable as a radio pulsar, as even a tenuous wind or corona will disperse the pulsed signal beyond detectability as was pointed out by van den Heuvel (1984). A scenario for millisecond pulsar formation and evolution (Xia et al, 1986) we proposed is shown in a schematic diagram, Fig 8. The "binary pulsars" (Type I) evolve along the track I first, then they will enter the "graveyard" along the evolutionary tracks for Type I pulsars when their periods are large enough. Before their companions fill their Roche lobe to start the accretion phase, these binaries would evolve further along the track II. The positions to start accreting is dependent on the evolutionary rate of their companions. At these point the "binary pulsars" would become observable X-ray binary pulsars with spun-up by accretion and then jump to the lower part of this figure because of their negative period derivatives.

The dots in the lower part of this figure are those for observed X-ray binary pulsars, that would evolve along the track III till their periods approach to P_{eq}. The accreted matter would be swung out by the centrifugal forces at that time, and the X-ray binary pulsars would become observable radio ones with very short periods. The advantage of this scenario is that the observed X-ray binary pulsars get their right place because of our evolutionary mode for Type I pulsars. We will discuss this scenario in detail elsewhere.

3.2. Radio Emission Mechanism for Two Types of pulsars

One of the most important parameters for pulsars is the radio luminosity. Gunn and Ostriker (1970) assume a model in which the radio lumi-

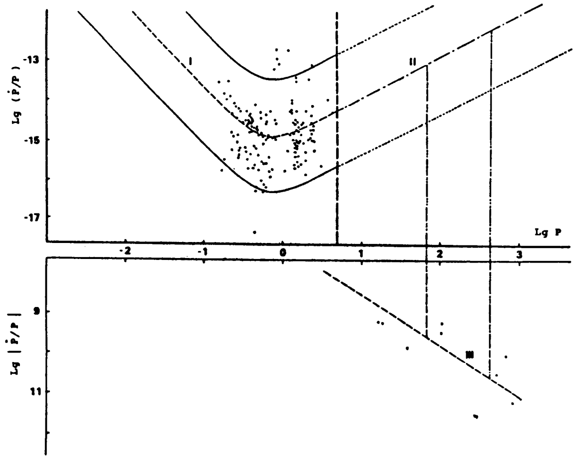

Fig. 8. Schematic diagram for millisecond pulsar formation

nosity is proportional to B^2, which was accepted by Lyne et al (1985). Proszynski and Przybycien (1985), however, tried to search the relation between the radio luminosity and $P, \dot{P}$ through non-parameter statistics which suggests that the pulsar radio luminosity various roughly as the cube root of the total loss of rotational energy. Pineault (1987) also tried to explore such a relation using statistical analysis, resulting in a relation of $L \propto B/P$.But the large dispersions over luminosities, periods and period derivatives make these results uncertain. Besides, a method like this has no abilities to clarify the dispute on the radio emission mechanism.

We are trying to do the same work but through a new approach, i.e., to fit in observational true age distributions. Considering the fact that the overwhelming majority of radio pulsars in the Galaxy can be detected with current searching techniques only if they lie within a kiloparsec or two of the sun, we can express the theoretical age distribution for pulsars within 5 kpc of the sun as follows

$$\frac{dN}{dt} \propto \frac{L(t)}{\left|\frac{dL}{dt}\right|} R(L)$$

here $L(t)$ is the radio luminosity of pulsars, $\frac{dL}{dt}$ the luminosity derivative, and R the birth rate.

Assuming that the radio luminosity of pulsars is related to P and $\dot{P}$ with the following formula

$$L = \alpha P^{a} \dot{P}^{b} (1 + 5 P^{3})^{c}$$

here α is coefficient, a, b, and c are constants to be determined. The factor $(1 + 5 P^3)$ was taken because the surface magnetic fields for Type I pulsars are given below

$$B_{s,I} = \left(\frac{3 c^3 I}{8 \pi^2 R^6} \frac{P \dot{P}}{1 + 5 P^3} \right)^{\frac{1}{2}}$$

Then the constants a, b, and c can be determined from the fitness as shown in Fig. 9. for Type II and Fig. 10 for Type I pulsars. The histograms in these two figures are observational true age distributions.

For Type II pulsars, we get $a = -1$, $b = 1$, and $c = 0$, suggesting that $L \propto B_s^2 / P^2$, or that the radio emission mechanism we should consider for Type II pulsars is the polar cap model. One by-product from this fitness is that the decay time scale, τ_D, must be larger than 5×10^6 yr, somewhere round 10^7 yr.

For Type I pulsars, we obtain two sets of values: $a = -6$, $b = 2$, $c = -1$; or $a = 1$, $b = 1$, $c = -1$, meaning that $L \propto B_L^2 \dot{P} / P$ or $L \propto B_s^2$. This result is consistent with that from multi-element regression analysis, but there may still have two possibilities. One is that we should consider both the polar cap model and the light cylinder model for Type I pulsars. The other is that the approach we use here may not be sensitive enough to distinguish the two mechanisms. We will discuss this problem elsewhere.

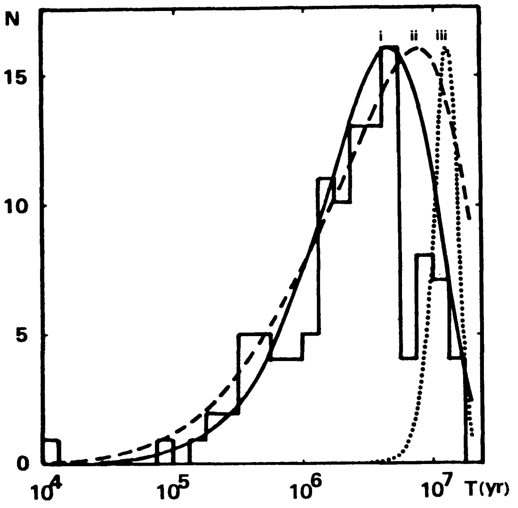

Fig. 9. Histogram of Type II pulsar ages, compared with the theoretical distributions for i) a=-1, b=1, c=0; ii) a=1, b=1, c=0; iii) a=-5, b=1, c=0

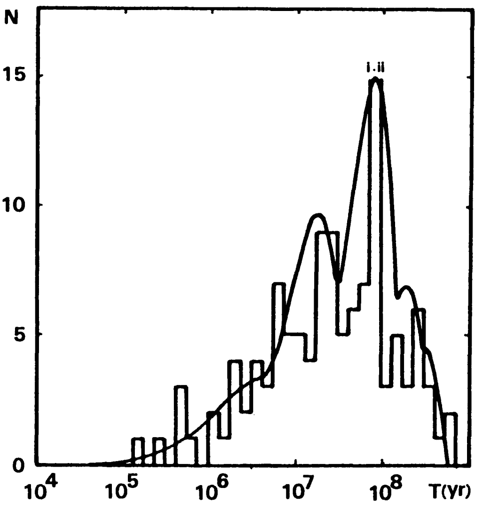

Fig. 10. Histogram of Type I pulsar ages, compared with the theoretical distributions for i) a= -6, b= 2, c = -1; ii) a = 1, b = 1, c = - 1

3.3. Kinematic Properties for Two Types of Pulsars

Following the way that Helfand and Tademaru took (1977) in their analysis, we find that the kinematic properties for our two types of pulsars just follow what was suggested by them. The average space velocities for Type I pulsars are about 40 - 50 km/sec, which is quite small as compared with that for Type II pulsars, 160 km/sec. (see the figures in Huang et al, 1987b)

Here we should point out that in analysing the space velocities for Type I pulsars, the data used are only those for ages of less than about 10^7 yr, while the ages for Type I pulsars are distributed over a range of 10^5 - 10^9 yr, because the predicted oscillation period available now is about 7×10^7 yr (Arnaud and Rothenlfug, 1981).

3.4. Interior Structures for Two Types of Pulsars

In a poster paper presented in this conference, we have shown two diagrams with very interesting features (see Fig. 1a and 2a in Huang et.al, 1987c). Fig. 1a in that paper illustrates a plot of lg $\frac{P}{\dot{P}}$ vs lg $\frac{P\dot{P}}{1+5P^3}$ for Type I pulsars, here $\dot{P}/P$ is a relative energy loss rate, $P\dot{P}/(1+5P^3)$ a quantity proportional to the surface magnetic fields for Type I.

The characetristic of this distribution is that it is dispersed over a very narrow band with a sharp cut-off at its right-hand side.

Fig. 2a (Huang et al, 1987c) is a diagram showing the relation between lg $P^2\dot{P}$ and lg $P\dot{P}$ for Type II pulsars, here $P^2\dot{P}$ is a quantity proportional to the magnetogyro ratio, and $P\dot{P}$ the one proportional to the surface magnetic fields for Type I. This distribution is characterized by its triangular dispersion with a cut-off at its left-hand side.

The important parameters entering the relations between the surface magnetic field and $P\dot{P}$ or $P\dot{P}/(1+5P^3)$ are radius, R, and moment of inertia, I, which means that the characteristic of these two distributions should have much something to do with these two parameters. Trying to get some information from these distributions may set certain constraints on the interior structures of neutron stars. A way to do this is the Monte-Carlo simulation.

Fig. 1b and 2b in our poster paper (Huang et al, 1987c) are two plots from Monte-Carlo simulation, both of which fit with their corresponding observational distributions quite well. The premise to get these fitnesses is that the coefficients in these two simulations must differ by an order of magnitude

$$< A_{II} > \approx 15 < A_I >$$

or

$$< B^2_{II} \left(\frac{R^6}{I}\right)_{II} > \approx 15 < B^2_I \left(\frac{R^6}{I}\right)_I >$$

If we use A_I for Type II simulation or vice versa, what we have will be totally different from the observational ones. To be typical pulsars of each type, it would be very hard to imagine that the interior structures are the same, but the surface magnetic fields are different, or vice versa.

But we have shown that (Huang et al, 1985) if the interior structures for typical pulsars of each type are different, soft EOS for Type II and stiff EOS for Type I, then their surface magnetic fields will be different, the resulting coefficient A for each type will be different too and it just satisfies the need for the Monte-Carlo simulation.

4. CONCLUDING REMARKS

In conclusion, the properties of two types of pulsars proposed by us can be summarized in Table 1.

TABLE 1 Basic Properties of Two Types of pulsars

Type	I	II
ρ_c	low	high
R	large	small
$R/I_{45}^{1/6}$	1.3 - 1.4	.65 - 1.05
EOS	stiff	soft

$\dot{P}$	$A P^{-1} + B P^2$ $B = 5 A$	$A \exp(-2t/\tau_D) P^{-1}$ 10^7
B_s	weak	strong
L	$B_L^2 \dot{P}/P$ B_s^2	B_s^2 / P^2
Emission Mechanism	Light Cylinder Model Polar Cap Model	Polar Cap Model
Evolution	dying of steep increase in P	dying of magnetic field decay
Origin	Collapse of accreting WD	SN II

Now the question is what causes the differences for these two types of pulsars? The very reasonable answer might be the origin of neutron stars. Here we would like to say that Type I pulsars might be formed through the collapse of accreting WD, and the explosion of SN II might create Type II pulsars. But in order to give you more conceivable picture, there are still a lot of work to be done.

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DISCUSSION

S. Kulkarni: If the age of Type I pulsars is as large as 10^9 y, then type I pulsars should form a relaxed system. Is the z-distribution of such pulsars consistent with this expectation? Are some of these pulsars returning back to the galactic plane?

J.H. Huang: Yes - indeed. The $|z|$-distribution of Type I pulsars really shows a pattern characteristic of a relaxed system. As you can see from the figure given above, a typical star has oscillated several times when the true age is larger than a few times 10^7 yr, which is consistent with the predicted oscillation period of about 7×10^7 yr. But the data for pulsars' proper motions are not sufficient for judging whether our determined ages for Type I pulsars are correct or not. We have to wait and see.

J. Shaham: Could you please elaborate some more on the role of $^3P_2$ neutron superfluidity in changing the slow-down pattern of pulsars?

J.H. Huang: In the interior of neutron stars, the $^3P_2$ superfluid neutrons should lose energy through interaction with the internal magnetic field. Then they will move out of the vortex axes without any change in their quantum number. In order to stabilize the superfluid neutron vortices, we assume that the Ekman pumping process may function, i.e., the normal neutrons in the vortex axes will move out and become superfluid ones, then the normal neutrons at the normal neutron layer will flow into the vortex axes. This is a way to transfer the rotational energy of neutron stars into superfluid vortices because there is an interaction between the magnetic moments of normal neutrons and electrons in the inner crust, and the relaxation time scale for this interaction is only seconds. This is how we imagine $^3P_2$ superfluid neutrons slow down the pulsars.

C. Alcock: While it is not possible to decide whether the equation of state is stiff or soft, it is difficult to believe that both types of EOS co-exist in nature. The reason for this is that at neutron star densities all reactions proceed to completion, and only one state is allowed.

J.H. Huang: If two different processes to create neutron stars exist, say, Type II SN explosion and the collapse of accreting WD, then the rather violent explosion of Type II SN may generate neutron stars with quite small radii and high central densities, i.e., with soft EOS while the rather mild collapse of the accreting WD may create neutron stars with large radii and low central densities, i.e., with stiff EOS. Of course, I can't prove it now, but it would be very hard to believe that different physical processes to create neutron stars lead to only one type of EOS.

G. Srinivasan: As we have heard, PSR 0655 may be very old, implying field saturation around 2×10^{10} Gauss. The three millisecond pulsars, on the other hand, have a magnetic field of 5×10^{8} Gauss. This suggests that the asymptotic field strength of neutron stars formed in accretion induced collapse of white dwarfs may be more than an order of magnitude smaller than that of neutron stars formed by direct core collapse. This, again, may be pointing to differences in structure and equation of state of these two types (or classes) of neutron stars.