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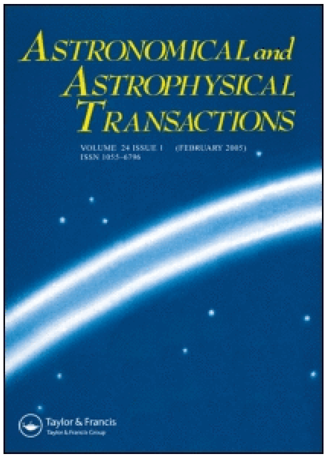

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"Recycled" white dwarfs?

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"RECYCLED" WHITE DWARFS?

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The observed magnetic strength and the spin period of single white dwarfs (WD) are analyzed. The analysis of thermal and spin evolution shows that almost all WDs with known parameters can be treated in terms of evolutionary scenario of so called recycled radio pulsars. In other words, it is suggested that most white dwarfs had passed through the accretion spin-up stage in close binary system.

KEY WORDS Magnetic white dwarfs, spin evolution

INTRODUCTION

It has become clear after discovering millisecond pulsars that some of them pass through the accretion state in close binary system (Srinivasan & van den Heuvel, 1982). Mainly this conclusion is based on the radio pulsar distribution on the p–$\dot{p}$ diagram (Kolosov, *et al.*, 1989). It is obvious from common evolutionary considerations that magnetized WDs can evolve according to an analogous scenario. However two questions arise:

1) How this statement can be verified if $\dot{p}$ for WDs is unknown?
2) What part of WDs population are recycled WDs?

In this work we have tried to answer these questions.

B–p DIAGRAM FOR SINGLE WDs

Unlike neutron stars (NS) there is a possibility of directly measuring the WD surface magnetic fields. In fact, the magnetic strength B or magnetic dipole moment μ ($\mu = BR^3/2$, where R is WD radius) for WDs, and the $\dot{p}$ for NSs, have the same sense. That is why the B–p diagram was chosen as an evolutionary diagram for the WDs. There are three basic regimes of interaction with environment for single magnetized WDs (Lipunov, 1987).

"E"—Ejector, $p_{\rm wd} < p_e$
"P"—Propeller, $p_e < p_{\rm wd} < p_a$
"A"—Accretor, $p_a < p_{\rm wd}$

The boundaries between them are determined by critical periods:

$$p_e \simeq 215 B_6^{1/2} R_9^{3/2} v_6^{1/2} m^{-1/2} \rho_{-24}^{-1/4}\ \text{sec} \tag{1}$$

$$p_a \simeq 1.7 * 10^5 B_6^{6/7} R_9^{18/7} v_6^{9/7} m^{-11/7} \rho_{-24}^{3/7}\ \text{sec} \tag{2}$$

where $B_6 = B/10^6G$, $R_9 = R/10^9$ cm and $m = M/M_\odot$ are WDs magnetic strength, radius and mass correspondingly, $\rho_{-24} = \rho/10^{-24}$ g/cm^3 is the density of the surrounding matter, $v_6/10^6$ cm/sec is the WDs velocity relative to the environment (or the velocity of the environment relative to the WD). Let us turn to the B–p diagram for the WDs with known parameters (Figure 1). The spin period p, and surface magnetic field B, for the WD were taken from (Shmidt, 1987). It follows from the diagram that three WDs lie in the region corresponding to "A" stage while the others lie in the region corresponding to "P" stage.

Age of WDs

Fortunately we have the independent method for the WD age determination. This method is based on the results of the WD cooling theory. The first approximating of this theory was considered by Schwarzschild (1958). The more correct analysis was made by Lamb & van Horn (1975), Sweeney (1976) and Shaviv & Kovetz (1976). They investigated colling of WD by quantitative method. Their results allowed us to determine the age of the investigated WDs with known temperatures (see Table 1).

Spin evolution of WDs

The evolution of a single magnetized WD is defined mainly by the equation for angular momentum change (Lipunov, 1987):

$$\frac{dIw}{dt} = -\kappa_t \frac{\mu^2}{R_t^3} \tag{3}$$

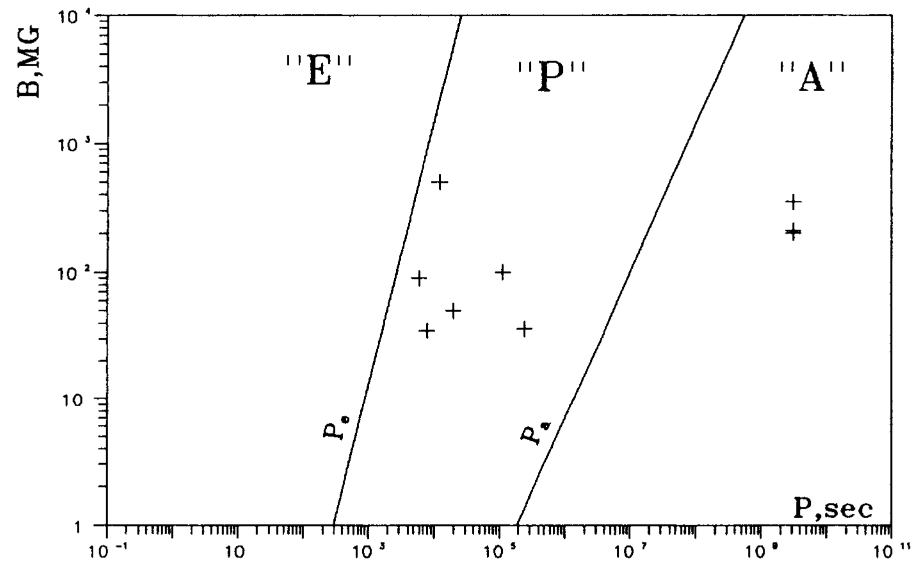

Figure 1 "B–p" diagram for WDs with known parameters. Both lines show critical periods.

Table 1

White Dwarf	*T, K*	*Age, yr*	*p*	p_{beg}, *s*	*B, MGs*
PG 1015 + 01	10,000	$6*10^8$	99 m	$4*10^3$	90
Feige 7	22,000	$6.3*10^7$	132 m	$7*10^3$	35
PG 1031 + 23	15,000	$2*10^8$	204 m	$9*10^3$	500
PG 1313 + 095	15,000	$2*10^8$	324 m	$2*10^4$	50
G 195-19	8,000	10^9	1.3 d	$9*10^3$	100
BPM 25114	20,000	$4*10^7$	2.8 d	10^5	36
G 240-72	6,000	$2.5*10^9$	>100 yr	$4*10^3$	200
GD 229	16,000	$2.5*10^8$	>100 yr	$4*10^4$	200
Grw + 70 8247	12,000	$4*10^8$	>100 yr	$2*10^4$	350

where I is the inertia moment of WD, $w = 2\pi/p$, κ_t and R_t, in general case, are determined by the regime of rotator interaction with environment (see Lipunov, 1987). For "P" and "A" stages (3) yields the following equations:
for the "P" stage:

$$p_{\rm beg}^{-1} - p_{\rm end}^{-1} = 10^{-13}\kappa_t m^{8/7} R_9^{-8/7} v_6^{-18/7} \rho_{-24}^{6/7} B_6^{2/7} t_{\rm yr} \qquad (4)$$

for the "A" stage:

$$p_{\rm end} - p_{\rm beg} = 10^{-3} m^{-2} R_9^4 B_6^2 t_{\rm yr}, \qquad (5)$$

Then we can estimate the initial period of WD using Eqs (4) and (5). The obtained results are shown in the Figure 2 (see also Table 1). It is easy to notice that the initial periods of WDs lie in a small region on the diagram. In order to explain this fact let us consider the WD spin evolution in close binary system at

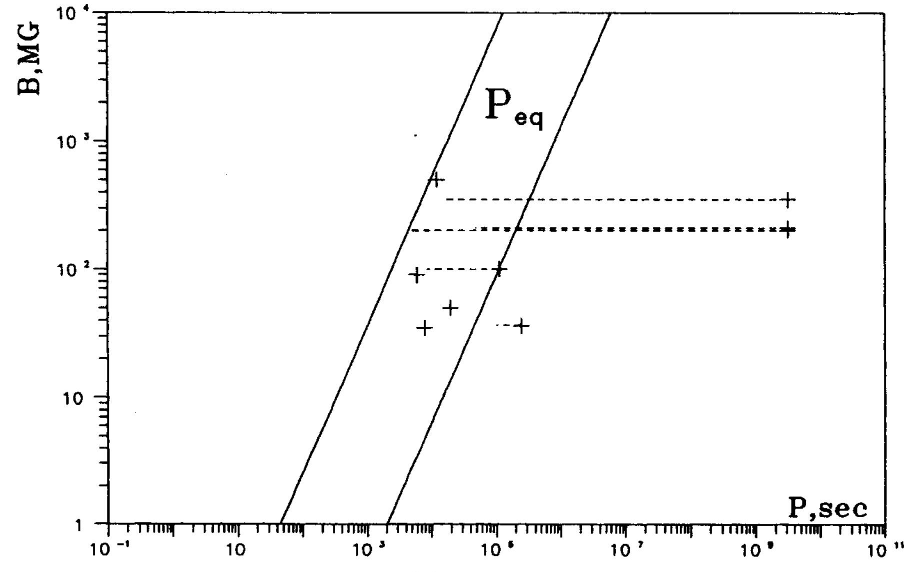

Figure 2 Evolutionary diagram for WDs with known parameters. The dashed lines are evolutionary tracks. The zone between thick lines corresponds to the state with equilibrium period.

the accretion stage. This evolution was considered in detail by Lipunov (1987) and Postnov (1985). We now consider only some main points following Lipunov (1987). The evolutionary equations for the spin period in this case may be written as follows:

$$\frac{dIw}{dt} = \dot{\mathrm{M}}(\mathrm{GM}R_{\mathrm{a}})^{1/2} - \kappa_t \frac{\mu^2}{R_{\mathrm{c}}^3} \tag{6}$$

where R_{a}—is the magnetospheric Alfven radius (it can be estimated from the condition $(\mu^2/(2\pi R_{\mathrm{a}}^6) = \rho v^2 = \dot{\mathrm{M}}(4\pi R_{\mathrm{a}}^2)^{-1}\ (\mathrm{GM}/R_{\mathrm{a}})^{1/2})$, and R_{c}—is the corotation radius given by $R_{\mathrm{c}} = (\mathrm{GM}/w^2)^{1/3}$. It is clear from (6) that WD must accelerate until equilibrium spin period p_{eq}, which is determined by the balance between the acceleration and deceleration torques. This gives:

$$p_{\mathrm{eq}} \simeq 1.8 * 10^3 B_6^{6/7} R_9^{18/7} m^{-5/7} \dot{\mathrm{M}}_{16}^{-3/7} \tag{7}$$

where $\dot{\mathrm{M}}_{16} = \dot{\mathrm{M}}/10^{16}$ g/sec is the accretion rate on WD.

Let $\dot{\mathrm{M}}_{16}$ be equal to $0.6 \div 60$ $(10^{-10} \div 10^{-8}\,\mathrm{M}_{\odot}/\mathrm{yr})$. Taking into account that parameters of WDs have some dispersion we obtain a corresponding error box on the B–p diagram. From Figure 2 one can see that the tracks of eight WDs pass through the equilibrium zone. So we can explain the observed distribution of WDs on B–p diagram by the following reason. All considered WDs except BPM 25114 have passed through the accretion spin up stage in close binary system. In order to verify this assumption let us estimate WDs relaxation time into equilibrium state:

$$t_{\mathrm{rel}} = \frac{Iw}{\dot{\mathrm{M}}(\mathrm{GM}R_{\mathrm{a}})^{1/2}} \tag{8}$$

Substituting $I \simeq \mathrm{M}R^2$ into (8) we obtain the relaxation time in the following convenient form:

$$t_{\mathrm{rel}} \simeq \left(\frac{R_{\mathrm{wd}}}{R_{\mathrm{c}}}\right)^2 \frac{\mathrm{M}}{\dot{\mathrm{M}}} \tag{9}$$

The last expression shows that the relaxation time is much less than the duration of mass exchange stage. The achievement to equilibrium state occurs most probably at the common envelope stage. The stage of cataclysmic variables seems more incredible because only one per cent of binary system can pass through this stage.

DISCUSSION

Analysis carried out above shows that practically all considered WDs can be accelerated in binary system. However, the following question is not answered: why these WDs are single now? The second component must be younger and, generally speaking, more hot in considered "recycled" scenario. If we assume nevertheless that the second component is cooled faster than the first one, and becomes invisible, then we have to assume that it must be 3 ÷ 5 times more massive (see for example Shapiro, Teukolsky, 1983). But it is improbable. The observable solitariness of WDs cannot be explained by means of binary system disintegrations only because the rate of such disintegrations is low. The peculiar selection effect can play some role in explaining this fact. All considered WDs have very strong magnetic fields. If we assume that these fields are generated only in very close binary system, then the absence of the second component is naturally explained by its absolute destruction. Another explanation of the observable solitariness of WDs can be as follows. All considered WDs passed through the accretion stage of cataclysmic binaries and when the mass of light secondary reached the mass $\sim 0.01\,M_\odot$, this component was destroyed (Paczynski, 1983; Ruderman, 1989).

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