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Velocity-Magnetic Field Correlation of Pulsars

Abstract

Monte Carlo simulations of the evolution of pulsars are carried out in order to compare with the recent measurement of the pulsar transverse velocity by Lyne & Lorimer (1994). The new electron density distribution model of Taylor & Cordes (1993) is adopted in the simulation. Accurate pulsar orbits in the Galactic gravitational field are calculated. It is found that the constant magnetic field model of pulsars can account for the new measurement of the pulsar transverse velocity, and the apparent correlation between the strength of the magnetic field and the transverse velocity of the pulsars. The present finding confirms the validity of the constant magnetic field model of pulsars, and consolidates the idea that the apparent correlation between the strength of the magnetic field and the transverse velocity of the pulsars is caused by observational selection effects.

I Introduction

We have recently shown, through the method of Monte Carlo simulations of the evolution of pulsars, that the constant magnetic field model of pulsars can account for the apparent correlation between the strength of the magnetic field and the transverse velocity of the pulsars (Itoh & Hiraki 1994). Their Monte Carlo simulation method is an extension of the one of Wakatsuki et al. (1992). Bhattacharya et al. (1992) also carried out Monte Carlo simulations of the evolution of pulsars and showed that the decay timescale of the pulsar magnetic field is longer than 10^8 yr.

As discussed by Itoh & Hiraki (1994), the problem of the observed correlation between the strength of the magnetic field and the transverse velocity of the pulsars is a long-standing problem discussed by many authors (Harrison & Tademaru 1975; Helfand & Tademaru 1977; Lyne, Anderson, & Salter 1982; Anderson & Lyne 1983; Radhakrishnan 1984; Cordes 1986; Stollman & van den Heuvel 1986; Bailes 1989; Narayan & Ostriker 1990).

Itoh & Hiraki (1994) used the observational data compiled by Harrison, Lyne, & Anderson (1993). Their work was a major addition to the previous radio interferometry

measurements of the proper motions of pulsars carried out by Anderson, Lyne & Peckham (1975), Lyne et al. (1982), Backer & Sramek (1982), Gwinn et al. (1986), Bailes et al. (1990), and Fomalont et al. (1992). Itoh & Hiraki (1994) succeeded in accounting for the observed correlation between the strength of the magnetic field and the transverse velocity of the pulsars. The reason for the apparent correlation has been due to the fact that old high-velocity pulsars escape observation because they are generally located far from the Galactic plane; thus, observed high-velocity pulsars tend to be young ones. On the other hand, there exists an apparent negative correlation between the characteristic age and the strength of the magnetic field, which is mainly due to the fact that the range of the observed pulsar periods is narrower than that of the observed pulsar period derivatives. Owing to these two apparent correlations, high-velocity pulsars appear to have strong magnetic fields.

Recently, Lyne & Lorimer (1994) reassessed the velocities of radio pulsars using the Galactic electron density distribution model of Taylor & Cordes (1993). They obtained significantly higher values for the pulsar velocity than reported by Harrison et al. (1993) on which Itoh & Hiraki's (1994) analysis has been based.

It is the purpose of the present paper to carry out new Monte Carlo simulations of the evolution of pulsars using Taylor & Cordes's (1993) electron density distribution model. We also calculate the pulsar orbits in the Galactic gravitational field accurately. We shall compare the Monte Carlo simulation results with the pulsar velocity data compiled by Lyne & Lorimer (1994).

II Observational data

In Figure 1, we show the observational data of the velocity-magnetic field correlation of pulsars. The data have been published in Lyne & Lorimer (1994) in a graphical form. The data have been provided to us by D.R. Lorimer in tabular form. The original data consist of 99 pulsars. We have excluded one millisecond pulsar and two binary pulsars, because these pulsars are considered to have experienced mass accretion from the companion star which might have significantly affected the magnetic field of the pulsars. Therefore, the remaining 96 pulsars have been taken into our analysis. Of these 96 pulsars, eight pulsars have only upper limits to their transverse velocities. Following Lyne & Lorimer (1994), we have assumed that these eight pulsars have half the values of the upper limits as the values of the transverse velocities.

The observed data of the 96 pulsars give the Spearman rank order correlation coefficient between the transverse velocity V_t and the strength of the magnetic field B

$$r_s = 0.171. \tag{1}$$

The strength of the magnetic field B is defined by

$$B = 3.2 \times 10^{19} (P\dot{P})^{1/2} \, \text{G}, \tag{2}$$
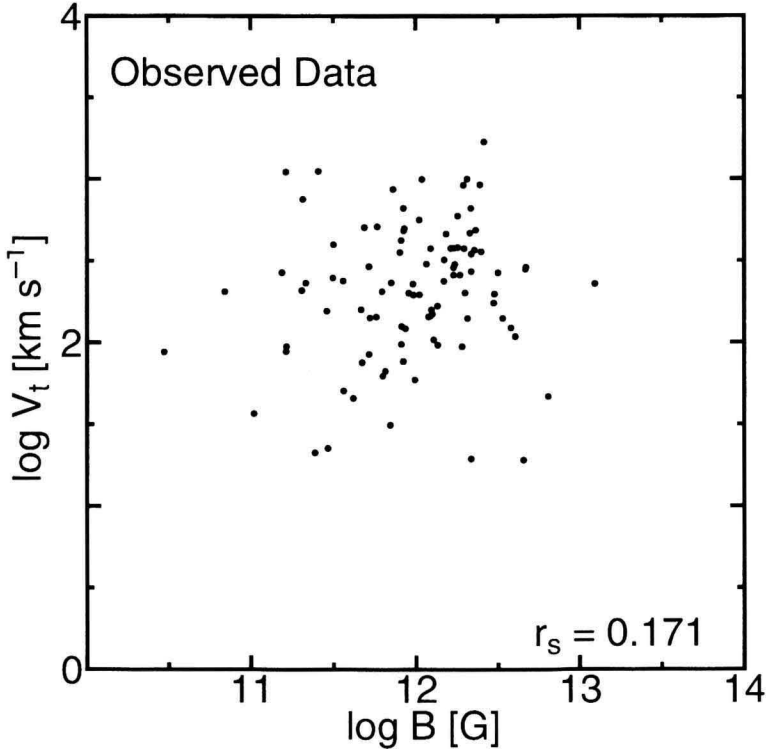
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Figure 1. Observed data of 96 pulsars for the transverse velocity and the strength of the magnetic field. The data are based on the tabular version of the paper of Lyne & Lorimer (1994).

corresponding to the pulsar radius $R = 1.0 \times 10^6$ cm and the pulsar moment of inertia $I = 1.0 \times 10^{45}$ g cm^2. In Eq. (2), the period P is measured in seconds, and the period derivative $\dot{P}$ is measured in seconds per second. This correlation is significant at the 91% level.

In Figure 2, we show the correlation diagram for the transverse velocity V_t and the characteristic age $P/2\dot{P}$. This diagram is essentially the same as Fig. 1 of Lyne & Lorimer (1994), except that we have excluded one millisecond pulsar and two binary pulsars. In Figure 3, we show the correlation diagram for the strength of the magnetic field B and the characteristic age $P/2\dot{P}$.

III Simulation results

The procedure of the Monte Carlo simulation is described in Itoh et al. (1995). As is done by Wakatsuki et al. (1992) and Itoh & Hiraki (1994), we optimize the adjustable
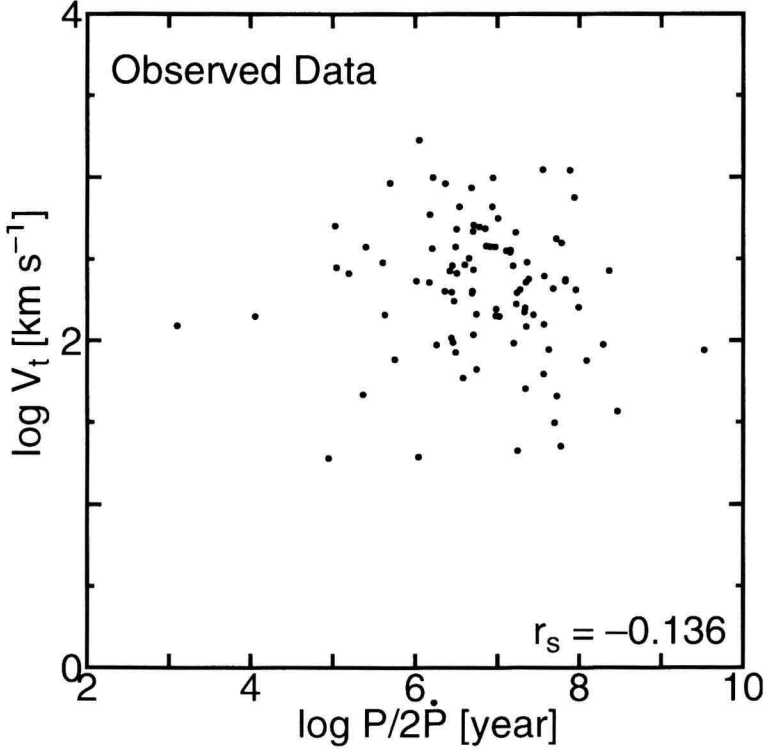
Figure 2. Observed data of 96 pulsars for the transverse velocity and the characteristic age.

parameters so that the simulation results produce the best fit for the distributions of P, $\dot{P}$, L_r, and V_t. The age of the pulsar is chosen randomly as $t \in (0, 5 \times 10^8$ yr$)$. In each simulation, we generate pulsars until we have detected 2000 pulsars. This is about 12 times the number of the observed pulsars with which we compare our simulation results. We adopt this method in order to minimize the Monte Carlo noise which is caused by the choice of different series of random numbers. We have confirmed by our Monte Carlo simulation that this number (2000 observed pulsars by simulation) is sufficiently large to stabilize the simulation results. This method was first adopted by Bhattacharya et al. (1992). Thus, the birthrate of the pulsars in the Galaxy r_b is defined as

$$r_b = \frac{164N/2000}{5 \times 10^8 \text{ yr}} \tag{3}$$

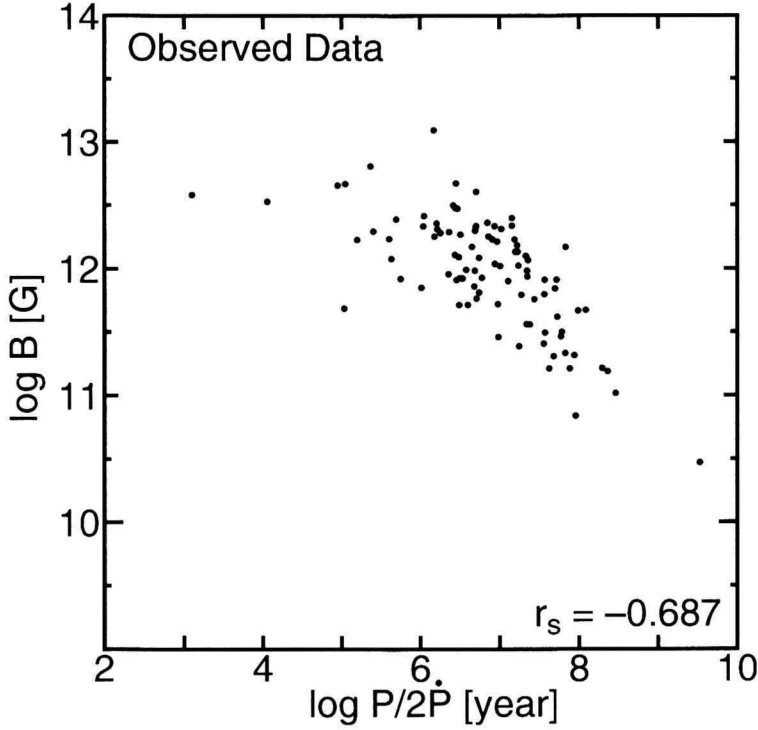where N is the number of the generated pulsars.

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Figure 3. Observed data of 96 pulsars for the strength of the magnetic field and the characteristic age.

In the following, we show an example of the simulation. First, we search for the best set of parameters that reproduce the observed distributions of periods, period derivatives, and radio luminosities as closely as possible. We adopt the following parameters: $\bar{P}_0 = 0.1$ s, $\sigma_u = 0.18$, $\bar{Q}_0 = 10^{-6.84}$ s$^{1/2}$, $\sigma_w = 0.45$, $\alpha_i = -2.28$, $\beta_i = 2.28/3$, $\gamma_i = 11.64$, $\sigma_\lambda = 0.8$, $\bar{s} = 2.60$, $\sigma_s = 0.45$, $r_b = 7.92 \times 10^{-3}$ yr^{-1}. The value of $\bar{Q}_0$ corresponds to $B = 3.3 \times 10^{12}$ G.

Next, we choose the pulsars which are located within 3 kpc from the Earth, and have the radio flux density at 408 MHz higher than 10 mJy, out of the simulated 2000 pulsars as the pulsars whose proper motion we wish to compare with the observation. In order to simulate the detectability of the proper motion of the pulsars, we employ the following method. If the proper motion of the simulated pulsar is greater than 7 mas-yr^{-1}, we take its velocity as the observed velocity. If the proper motion is smaller than 7 mas-yr^{-1}, we take 7 mas-yr^{-1} as the upper limit of the proper motion and deduce the corresponding upper limit for the velocity. Then we take half of these upper limit values as the velocities of the simulated pulsars. This procedure simulates the real proper-motion measurement (Harrison et al. 1993), 7 mas-yr^{-1} being the typical error.
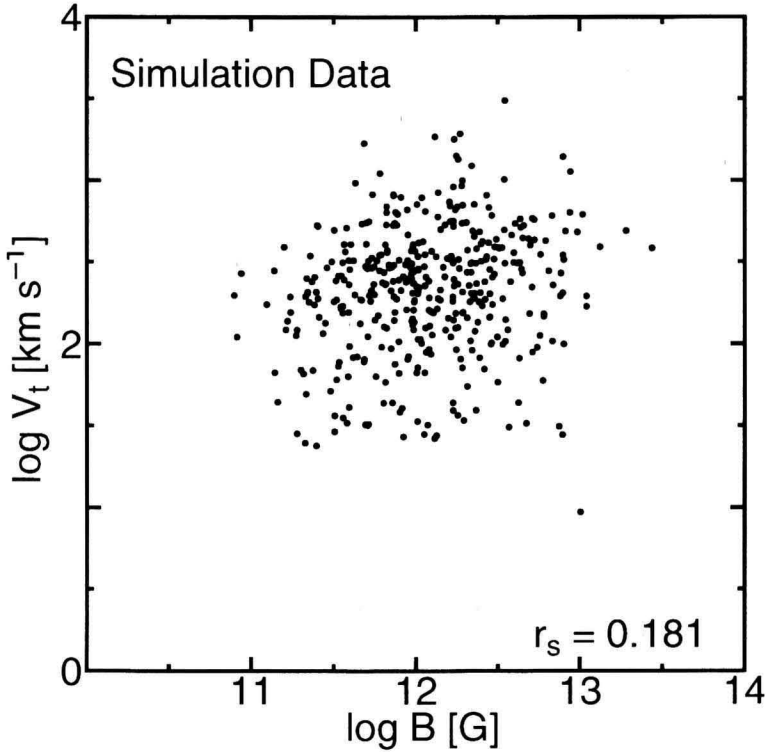
Figure 4. Correlation diagram of the strength of the magnetic fields and the transverse velocity of the simulated pulsars.

In Figure 4, we show the correlation diagram of these 411 pulsars. The Spearman rank order correlation coefficient between the transverse velocity and the strength of the magnetic field is $r_s = 0.181$. This result is in essential accord with the observational data presented in Section 2. Therefore, we reach the conclusion that the observed correlation between the transverse velocity and the strength of the magnetic field can be accounted for by the ordinary pulsar model of constant magnetic field.

The apparent correlation is caused by the selection effects. Old high-velocity pulsars escape observation because they are generally located far from the Galactic plane; thus, observed high-velocity pulsars tend to be young ones. On the other hand, there exists an apparent negative correlation between the strength of the magnetic field and the characteristic age, which is mainly due to the fact that the range of the observed pulsar periods is very much narrower than that of the observed pulsar period derivatives. In Figure 5, we show the apparent negative correlation between the transverse velocity and the characteristic age for the simulated pulsars. In Figure 6, we show the apparent negative correlation between the strength of the magnetic field and the characteristic age for the simulated pulsars. The observational data for the 96 pulsars of these
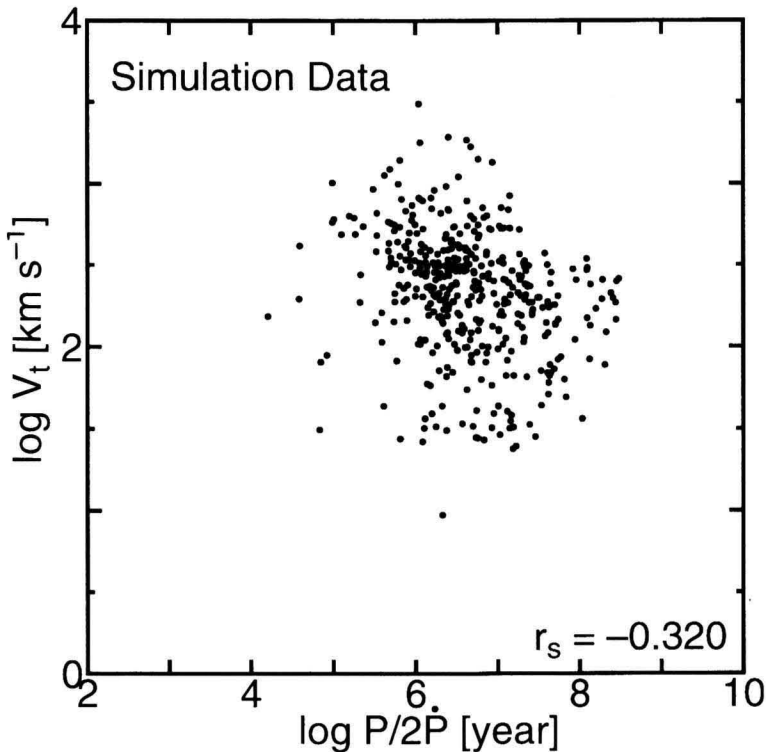
Figure 5. Characteristic age and transverse velocity of the simulated pulsars.

correlations are shown in Figs. 2 and 3. Owing to these two apparent correlations, high-velocity pulsars appear to have strong magnetic fields.

Stollman & van den Heuvel (1986) were the first to attempt to examine whether the velocity-magnetic field strength correlation of pulsars may arise due to selection effects. They concluded that the observed correlation at that time cannot be explained by selection effects. Their Monte Carlo simulation method differs from the present one in various ways, such as a different temporal behavior of the magnetic field strength, a different functional dependence of the pulsar radio luminosity on the period and period derivative, and a different treatment of the pulsar proper motion. However, the most important difference appears to be the observational data of the pulsar transverse velocity. Stollman & van den Heuvel (1986) used the data of Anderson & Lyne (1983) which included 26 pulsars. The correlation coefficient between the transverse velocity and the magnetic field strength of those 26 pulsars is 0.63. This high correlation coefficient no longer exists in the most recent data of Lyne & Lorimer (1994) with which we have compared our Monte Carlo simulation results.
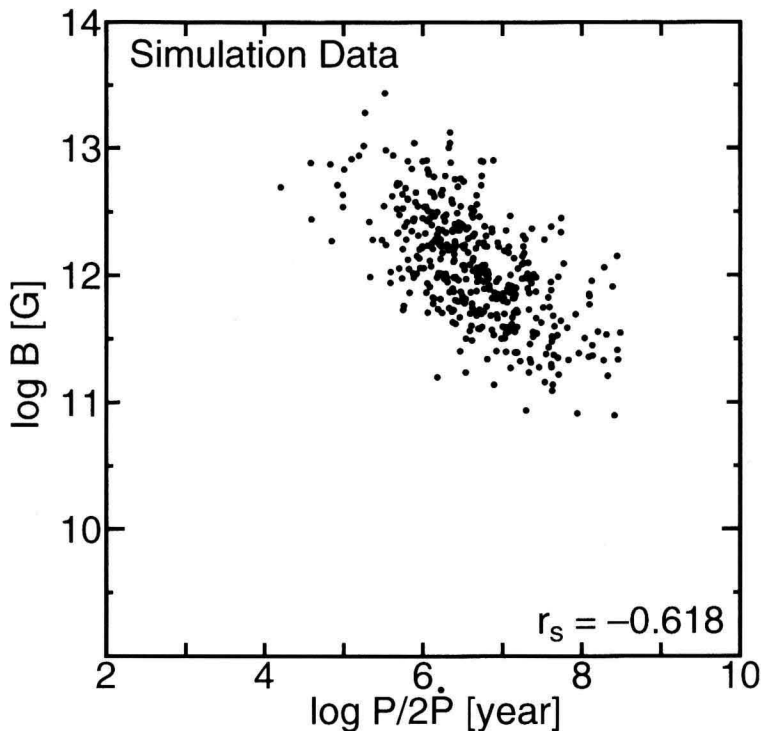
Figure 6. Characteristic age and strength of the magnetic field of the simulated pulsars.

Stollman & van den Heuvel (1986) have, however, pointed out that the correlation coefficient of order 0.2 can be reproduced by their Monte Carlo simulations.

IV Concluding remarks

We have carried out Monte Carlo simulations of the evolution of pulsars based on the constant magnetic field model in order to investigate the apparent correlation between the strength of the magnetic field and the transverse velocity of the pulsars. There exist three important improvements made upon our previous work (Itoh & Hiraki 1994). First, we have used the observational data of the pulsar transverse velocities of Lyne & Lorimer (1994), which are significantly more accurate than the previous data of Harrison et al. (1993), which have been used by Itoh & Hiraki (1994). Second, we have used the Galactic electron density distribution model of Taylor & Cordes (1993), which is remarkably more detailed than the electron density distribution model of Manchester used by Itoh & Hiraki (1994). Third, we have calculated the pulsar orbits in the Galactic gravitational field accurately using the potential of Hartmann et al. (1990).

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In this paper, we have confirmed the conclusion reached by Itoh & Hiraki (1994) that the apparent correlation between the strength of the magnetic field and the transverse velocity of the pulsars is caused by observational selection effects. Old high-velocity pulsars are biased against the observation because they are generally located far from the Galactic plane. The lack of the sample of the old high-velocity pulsars causes the apparent correlation in the observed data of the strength of the magnetic field and the transverse velocity of the pulsars, because old pulsars appear to have weak magnetic fields.

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