Initial Periods of Millisecond Pulsars

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Abstract Millisecond pulsars are accelerated to such short periods by accretion of matter and angular momentum from their companion. It is important to know the initial periods of millisecond pulsars, since this quantity is closely related to the accretion process and the equation of state of neutron star matters. For some millisecond pulsars, the initial period can not be neglected in the calculation of their characteristic ages, otherwise their characteristic ages will be greater than the Galaxy age. Based on off-centered dipole radiation theory, the initial periods of millisecond pulsars can be obtained, and the initial periods are found to be comparable to the current values.

1 Introduction

Millisecond pulsars are formed by accretion of matter from their companions in the binaries (van den Heuvel 1987), which is different from the process creating normal pulsars, so their magnetic field strength, rotation periods and period derivative differ remarkably from the corresponding quantities of normal pulsars. As first noted by Shklovsky (1970), for near pulsars the high transverse velocity may contribute to the period derivative. Camilo et al. (1994) found after the correction of their high transverse velocity, the corrected ages of several millisecond pulsars are older than the age of the Galactic disk. They reconcile this apparent paradox by suggesting some millisecond pulsars were born with periods close to their current periods. In order to find sub-millisecond pulsars, Edwards et al. (2001) surveyed 19 globular clusters, but they discovered none. The new X-ray observation of Crab (Weisskopf et al. 2000) and Vela pulsar (Pavlov et al. 2001) indicate the proper motion direction, the asymmetric axis of nebula and the jet direction are coincident. The polarization observations of those two pulsars at radio frequencies also indicate the spin axis and the proper motion is parallel in projection on the plane of sky (Deshpande et al. 1999; Moffett & Hankins 1999). These facts are strong support of the off-centered dipole radiation theory (Lai, D. et al. 2001; Harrison & Tademaru 1975). According to this theory, the velocity at the end of acceleration is a strong function of the initial period of pulsars. For these pulsars whose velocities have been measured, we can got their initial periods. It is obvious the period derived is the lower limit because we assume the last velocities are the result of asymmetric electromagnetic radiation, which dredge up the rotation energy.

2 The Acceleration of Pulsars by Off-centered Dipole Radiation

Harrison & Tademaru (1975) showed that the electromagnetic radiation from an off-centered magnetic dipole imparts a kick to the pulsars along its spin axis. This acceleration is attained on the initial spindown time scale of the pulsar. The spindown luminosity is

$$L = \frac{2\Omega^4}{3c^3}(\mu_\rho^2 + \mu_\phi^2 + \frac{2\Omega^2 s^2 \mu_z^2}{5c^2})\,, \tag{1}$$

where Ω is the angular rotation frequency of pulsar, the μ_ρ, μ_ϕ and μ_z, are components of the magnetic momentum, s is the distance of dipole center to the pulsar center. Another effect of off-centered radiation is the asymmetry of the emission intensity from the two poles. This asymmetric intensity can give a force to the pulsar

$$F = \frac{8}{15}(\frac{\Omega s}{c})\frac{\Omega^4 \mu_z^2 \mu_\phi^2}{c^4}, \tag{2}$$

For a typical situation, $\mu_\rho^2 \sim \mu_\phi^2 \sim \mu_z^2$, the asymmetry parameter $\varepsilon \equiv F/(L/c)$ is $0.4(\Omega s/c)$. For a given Ω the maximum $\varepsilon = 0.63$ is achieved when $\mu_\rho^2/\mu_z^2 = 0$ and $\mu_\phi^2/\mu_z^2 = 0.4(\Omega s/c)$. From

$$M\dot{V} = \varepsilon(L/c) = -\left(I\Omega\dot{\Omega}\right)/c\,, \tag{3}$$

we can get the kick velocity

$$V = 140R_{10}^2(\frac{s}{10\,\mathrm{km}})(\frac{\nu_i}{1\,\mathrm{kHz}})^3[1-(\frac{\nu}{\nu_i})^3]\,\mathrm{km/s}\,, \tag{4}$$

where the R_{10} is radius of pulsar, ν_i is the rotation frequency of pulsar at birth, ν is the rotation frequency at present. If we assume $s = 10\,\mathrm{km}$, equation (4) can be expressed in another way

$$\nu_i = (\nu^3 + \frac{V}{140(\frac{s}{10})R_{10}^2})^3\ \mathrm{kHz}\,, \tag{5}$$

Usually the diameter of a typical neutron star is $20-30\,\mathrm{km}$, so we assume the radius R_{10} to be 1. If $s = 10\,\mathrm{km}$, we can get the initial period and rotation frequency from equation (5).

3 The Initial Periods of Millisecond Pulsars

It is believed millisecond pulsars are formed through different process from that of normal pulsars, most of millisecond pulsars lie in the binary systems, the accreted material from the companion form a disk around the pulsar, and the accretion of this matter accelerated the pulsar to milliseconds. The velocity of millisecond pulsars are about one third of normal pulsars (Toscano et al. 1998). The parameters of millisecond pulsar are given in Table 1, these four columns are pulsar name, velocity in km/s, period in ms, and initial period in ms respectively. It is obvious the initial periods of millisecond pulsar are close to their current present observed period, for most of millisecond pulsars, it is about 30 percent of the current period. The shortest initial period is 0.8 ms and the longest is 2.1 ms. For the fastest rotational pulsar PSR B1937+21, the initial period is 0.777 times of its present period.

Table 1 The initial period of millisecond pulsars

PSR J-	velocity(km/s)	period(ms)	p_0(ms)
0437-4715	120.5	5.757	1.0513
0613-0200	77	3.062	1.2205
0711-6831	78	5.491	1.2153
1024-0719	62	5.162	1.3119
1045-4509	52	7.474	1.3912
1300+1240	284	6.219	0.79
1455-3330	100	7.987	1.1187
1603-7202	27	14.842	1.7308
1643-1224	159	4.622	0.9585
1713+0747	28	4.57	1.71
1730-2304	51	8.123	1.4002
1744-1134	33	4.075	1.6188
1857+0943	17	5.362	2.0194
1911-1114	183	3.626	0.9146
1939+2134	79	1.558	1.2101
1959+2048	190	1.607	0.9032
2019+2425	83	3.935	1.1904
2051-0827	14	4.509	2.1544
2124-3358	53	4.931	1.3823
2129-5721	56	3.726	1.3572
2145-0750	38	16.052	1.5445
2317+1439	94	3.445	1.142
2322+2057	80	4.808	1.2051

The closeness of initial period and the current period have great importance for millisecond pulsars. We get the initial period from the velocity considerations, but our results are in agreement with Camilo et al. (1994) who arrived at the same conclusion by considering the oldest pulsar must be younger than the Galaxy.

A few factors may contribute to the velocity of pulsars, including orbital velocity of its progenitor, asymmetric neutrino and hydrodynamic kick when the neutron star was born and asymmetric dipole radiation after the neutron star was born. Because millisecond pulsars are still in the binary the contribution by these three effects are not as big as that imparts to normal pulsars. Assuming the off-centered dipole radiation is the only factor, we should get the lower limit of the initial period.

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