Chin. J. Astron. Astrophys. Vol. 3 (2003), No. 2, 166–174
(*http://www.chjaa.org* or *http://chjaa.bao.ac.cn*)

Chinese Journal of
Astronomy and
Astrophysics

An Estimation of the Initial Period of Pulsars *

Zhan-Kui Huang [1,2] and Xin-Ji Wu [1,2,3]

[1] Department of Astronomy, Peking University, Beijing 100871; wuxj@bac.pku.edu.cn
[2] Chinese Academy of Sciences-Peking University Joint Beijing Astrophysics Center, Beijing 100871
[3] National Astronomical Observatories, Urumqi Astronomical Observatory, Chinese Academic of Science, Urumqi 830011

Received 2002 August 27; accepted 2002 December 30

Abstract The initial period of a pulsar is an important factor in our understanding of the formation of neutron stars and of the nature of the equation of state of neutron star matter. Up to now this quantity can only be obtained for a few pulsars for which accurate age and braking index are known. Based on the theory of the off-center dipole emission, in which pulsars obtain their high velocities depending on the initial periods, we calculate the initial period using the proper motion data. Because the orbital velocity of the progenitor and asymmetric kick in the supernova explosion may also contribute to the observed velocity of the pulsar, the derived values of initial periods are lower limits. For normal pulsars, the initial periods are in the range of $0.6 \sim 2.6$ ms. For the millisecond pulsars, the initial periods are comparable to their current periods, and the ratio between the initial period and the current period increases with the decrease of the current period. For PSR B1937+21 with the shortest period of 1.56 ms, the ratio is 0.77.

Key words: pulsars — stars: neutron

1 INTRODUCTION

Pulsars are rotating neutron stars that are born in supernova explosions. The shortest rotation period is a very important parameter for understanding the nuclear force and the structure of neutron stars. The shortest observed period is 1.56 ms belonging to PSR B1937+21. The upper limits of mass and rotation rate are of great interest to the theorists. Pulsars with the softest equation of state would have the shortest rotation period. Friedman et al. (1984) found that pulsars with the softest state equation can rotate with a period as short as 0.4 milliseconds. It had been expected to find new pulsars with periods less than 1 ms, so the announcement of the discovery of the 0.5 millisecond pulsar in Supernova 1987A brought great excitement to the theorists, although it failed to be detected in the remnant of Supernova 1987A in the follow-up

---

* Supported by the National Natural Science Foundation of China.

observations. In an attempt to find sub-millisecond pulsars, Edwards et al. (2001) surveyed 19 globular clusters, but none was discovered.

Assuming a constant braking index, by integrating the standard spin-down expression $\dot{\nu} \propto \nu^n$ (where $\nu \equiv 1/p$), the characteristic age of a pulsar can be calculated by the formula

$$\tau = \frac{1}{(n-1)} \frac{p}{\dot{p}} \left[1 - \left(\frac{p_0}{p} \right)^{n-1} \right], \tag{1}$$

where n is the braking index, p is the current period of pulsar, p_0 is the initial period, and $\dot{p}$ is the derivative of period. If the accurate age of a pulsar is known by other methods and the braking index is measured, then we can also use Eq. (1) to calculate the initial period. However, up to now there are only five pulsars with known braking indices (Zhang et al. 2000; Lyne 1994), all five indices are constant and are in the range 1.41–2.91. There are three pulsars with accurate ages and braking indices, namely, the Crab pulsar, PSR J0537–6910 and PSR J1811–1925; their initial periods are 19 ms (Manchester et al. 1977), 16 ms (Marshall et al. 1998) and 62 ms (Kaspi et al. 2001), respectively.

Many factors have been proposed to account for the fact that the observed braking index is not equal to 3. These factors include a non-dipolar field structure, secular evolution of the field strength (Blandford et al. 1983; Blandford & Romani 1988), change of the magnetic inclination angle (Qiao et al. 1985), and torquing by a disk surrounding the pulsar produced by supernova fallback (Menou et al. 2001). Lyne et al. (1996) pointed out that part of the torque on the pulsar is due to outflow of particles. Especially in the case of the Vela Pulsar, series of glitches may have produced a cumulative effect on the magnetic field or the effective momentum of inertia. The factors mentioned above indicate that the rotation energy cannot be transferred completely to the magnetic dipole radiation. The momentum of inertia, momentum of magnetic inertia and the inclination angle may evolve in the life of a neutron star, whereas they are assumed to be constant in Equation (1), hence the application of Equation (1) is conditional and we should only take it as providing a rough estimate rather than a standard scale. Assuming a relation between the initial period and the dynamo-generated magnetic field of pulsars, Xu et al. (2002) obtained initial periods statistically, with most probable periods lying between 20 and 30 ms.

Atoyan (1999) suggested that the origin of the relativistic electrons in the Crab nebula can be naturally explained as a relic population of the pulsar wind, which have lost most of their energy in the expanding of the nebula because of intensive radiation and adiabatic cooling. The observed radio spectrum of the Crab pulsar suggests that the initial slowing-down time of the Crab pulsar was $\tau_{\rm sd} \leq 30\,{\rm yr}$, implying that its initial period is about 3–5 ms, which is several times shorter than that given by the magnetic dipole emission model.

Pulsars have much higher velocities than their progenitors. Radhakrishnan (1992) classified pulsar acceleration theories into pre-natal, natal and post-natal depending on when the neutron star obtains its initial velocity. In the pre-natal category (Gutt et al. 1970), most pulsars are created in massive binary systems. When the supernova explosion takes place, the binary is broken up and the pulsar is born with the orbital velocity of its progenitor (Blaauw 1961). This model cannot explain the parallelism between the proper motion and spin axis, because the orbital velocity is perpendicular to the spin axis. Another difficulty for this theory is how to produce high velocity of several hundreds kilometers per second, when the orbital velocities are tightly distributed around a low value ($\sim 150\,{\rm km\ s^{-1}}$). In the natal category, a pulsar receives a randomly oriented kick at birth due to conservation of linear momentum in a slightly asymmetric explosion (Shklovskii 1970). Some authors (Arras & Lai 1999a, b) attributed the velocity to neutrino emission in the magnetic field and others (Herant et al. 1994; Burrows et al. 1995), to the kick of hydrodynamical driving. However, numerical simulation by Burrows et al. (1996) indicates that convection instability is not adequate to account for any kick velocities greater than 100 km s^{-1}. For the neutrino-produced natal-kick theory, the resulting kick velocity is $V_{\rm kick} \approx 50B_{15}$ km s^{-1}. Kicks of a few hundreds km s^{-1} would require the neutron star to possess a magnetic field of greater than 10^{15} G (Lai et al. 2001), which is almost inconceivable.

Harrison & Tademaru (1975) pointed out that off-center radiation can give a force to the neutron star in the direction of the spin axis and this force can accelerate the pulsar to a velocity of hundreds even a thousand kilometers per second. In this model, the velocity of the pulsar and the initial period are strongly correlated. This theory may provide a method to determine the initial period.

Compared to the other two models, the off-center dipole radiation model is much more accurate and its conclusion can be checked by available observational data. Its main consequence is that the direction of motion of the pulsar is along the spin axis. Pskovsky & Dorofeev (1989) proposed a method to test the post-natal acceleration theory and found that the existing data are in agreement with it. The most recent strong support comes from the X-ray observations of Crab pulsar and Vela pulsar (Weisskopf et al. 2000; Pavlov et al. 2001), which indicate that the proper motion, the asymmetric axis of nebula and the jet all coincide in their directions. The polarization observations of these two pulsars at radio frequencies also indicate that the spin axis and proper motion are parallel when projected on the plane of the sky (Deshpande et al. 1999; Moffett & Hankins 1999).

2 OFF-CENTER DIPOLE RADIATION AND METHOD OF CALCULATING INITIAL PERIOD

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

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

where Ω is the angular frequency of the pulsar, μ_ρ, μ_ϕ and μ_z are the cylindrical components of the magnetic momentum, s is the distance from the dipole center to the pulsar center. The off-center radiation can increase the luminosity by

$$\left(L - L_{s=0}\right)/L_{s=0} = 2\Omega^2\mu_z^2 s^2/5c^2(\mu^2 - \mu_z^2)\,. \tag{3}$$

Another effect of off-center radiation is an asymmetry in the emission intensity from the two poles. Such an asymmetric intensity can give a force to the pulsar,

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

This force can accelerate the pulsar along the direction of the spin axis during the spindown. For a typical situation, $\mu_\rho \sim \mu_\phi \sim \mu_z$, the asymmetry parameter $\varepsilon \equiv F/\left(L/c\right)$ is $0.4\,(\Omega s/c)$. From

$$M\dot{V} = \varepsilon(L/c) = -(I\Omega\dot{\Omega})/c \tag{5}$$

we can obtain the kick velocity

$$V = 140 R_{10}^2 \left(\frac{s}{10\ \text{km}}\right) \left(\frac{\nu_i}{1\ \text{kHz}}\right)^3 \left[1 - \left(\frac{\nu}{\nu_i}\right)^3\right] \text{km s}^{-1}, \tag{6}$$

where R_{10} is the pulsar radius in units of 10 km, ν_i the rotation frequency of the pulsar at birth, ν the rotation frequency at present. Equation (6) can be expressed in another way to give the initial frequency as a function of the pulsar velocity:

$$\nu_i = \left(v^3 + \frac{V}{140\left(\frac{s}{10}\right) R_{10}^2}\right)^{1/3}, \tag{7}$$

where V is the transverse velocity. Since the true space velocity of a pulsar cannot be obtained unless the angle between the line of sight and the spin axis is known. On average, if the velocity distribution is isotropic, the space velocity should be about 1.22 V.

3 THE DATA

The velocity of the pulsars can be estimated by the observations of proper motion (Taylor et al. 1993; Stinebring et al. 2000) and the scintillation (Wang et al. 2001) of pulsars. To examine the difference between normal pulsars and millisecond pulsars (MSPs), we analyze these two groups separately. Most of the proper motion velocities of pulsars are from Taylor et al. (1993) and the proper motion data of MSPs are from Toscano et al. (1998). For some pulsars, we adopt the proper motion data from the latest literature, such as PSR B1951+32 (Migliazzo et al. 2002), PSR J1811–1925 (Kaspi et al. 2001), and PSR B1957–24 (Ganesler et al. 2000).

The pulsar velocity is derived from $V = 4.74\mu D\,\text{km s}^{-1}$ (Lorimer et al. 1997), in which μ is the proper motion in mas yr^{-1} and D is the distance in kpc. There are only about 20 pulsars that have accurate annual parallax measurements (Chatterjee 2001) for the distance. In this group, the highest velocity is 631 ± 35 km s^{-1}, and the mean velocity is 167 km s^{-1}.

For most other pulsars the distance is derived from the dispersion measure, which is a function of the electron density along the line of sight. Because of the complexity of the distribution of ionized matter, the distance derived from the dispersion measure is not so reliable as that from the annual parallax. An accurate velocity of PSR B2224+65 is difficult to obtain, because it is inside a significant amount of ionized material, and the dispersion measurement may be biased upward, leading to the distance being overestimated (Chatterjee et al. 2002).

The VLA measurements of proper motion are very effective, but for pulsars located in low latitudes the accuracy was restricted by observations. This effect is serious for PSR B0736–40 and PSR B0833–45 (Fomlalont et al. 1992, 1997). The velocities of PSR B0736–40 from different measurements of proper motion are 770 km s^{-1} (Fomlalont et al. 1992) and 570 km s^{-1} (Fomlalont et al. 1997) respectively. The time baseline of the latter observation is twice that of the former, so we adopt the latter measurement. The proper motion of PSR B0833–45 measured with VLA is 58 mas yr^{-1} (Legge 2000) and is 46 mas yr^{-1} measured with Hubble Space Telescope (Caraveo et al. 2001). For a distance of 0.294 kpc, the velocity is 80 km s^{-1} and 65 km s^{-1} respectively. We adopt the Hubble measurement because it is model-free.

For PSR B1957–24, a dramatic correction has been made from new velocity measurement. The previous velocity was derived from the distance between the center of the supernova remnant and the current position of the pulsar and from the characteristic age, the result is 1500–1900 km s^{-1}. The VLA observation separated by 6.7 years, however, indicates that the velocity is only one-third of the former value. This measurement is much more reliable, so we adopt it in this paper.

4 THE INITIAL PERIOD OF NORMAL PULSARS

The parameters of normal pulsars are given in Table 1. The first column is the pulsar name, the second is the velocity calculated from $V = 4.74\mu D$ km s^{-1}, the third is the period in seconds, and the fourth is the initial period in ms obtained by the method described in Section 2. PSR B2224+65 has the shortest initial period of 0.52 ms. As mentioned above, because the distance to this pulsar and the velocity are overestimated, the derived initial period is biased toward a lower value. The initial periods of the other pulsars are distributed in a narrow range between 0.6 ms and 2.6 ms: 60 of the pulsars have periods shorter than 1 ms, 10 between $0.6 \sim 0.7$ ms and 24 between $0.7 \sim 0.8$ ms. The histogram of the initial periods is presented in Fig. 1. As we discussed in the previous section, pulsars of the shortest periods are those with the highest velocities.

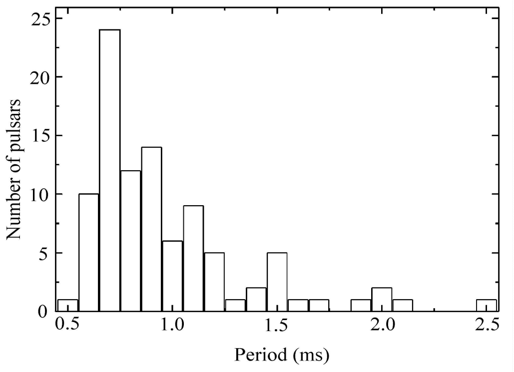

Fig. 1 Initial period distribution of normal pulsars.

Although the coincidence between the jet direction, the rotation axis and the proper motion of pulsars is evidence for the off-center asymmetric dipole radiation model, we cannot completely rule out possible contributions from the asymmetric kick in supernova explosion and from their progenitor orbital velocity. Since the observed velocity may be a combination of all three, the initial period presented in this paper are lower limits. Because of the difficulties in estimating their relative contribution to the velocity, we simply assume that each contributes one-third to the velocity, then the initial period for PSR B2224+65 changes to 0.9 ms.

5 THE INITIAL PERIOD OF MSPs

It is believed that MSPs are formed through a process different from normal pulsars. Most of MSPs are in binary systems. The accreted material from the companion forms a disk around

Table 1 Initial Period of Normal Pulsars

PSR J	V (km s^{-1})	P (s)	$p(0)$ (ms)	PSR J	V (km s^{-1})	P (s)	$p(0)$ (ms)
0139+5814	301	0.272	0.78	1543+0929	144	0.748	0.99
0151–0635	307	1.465	0.77	1543–0620	60	0.709	1.33
0152–1637	307	0.833	0.77	1559–4438	110	0.257	1.08
0206–4028	316	0.631	0.76	1604–4909	511	0.327	0.65
0255–5304	382	0.448	0.72	1607–0032	20	0.422	1.92
0304+1932	167	1.388	0.94	1645–0317	36	0.388	1.57
0323+3944	237	3.032	0.84	1709–1640	15	0.653	2.11
0332+5434	145	0.715	0.99	1720–0212	316	0.478	0.76
0358+5413	77	0.156	1.22	1749–28	43	0.563	1.48
0450–1248	46	0.438	1.44	1752–2806	68	0.563	1.27
0452–1759	282	0.549	0.79	1757–2421	587	0.234	0.62
0454+5543	205	0.341	0.88	1807–0847	85	0.164	1.18
0502+4654	95	0.639	1.14	1820–0427	314	0.598	0.76
0525+1115	452	0.355	0.68	1823+0550	77	0.753	1.22
0528+2200	228	3.746	0.85	1825–0935	120	0.769	1.05
0534+2200	153	0.033	0.97	1840+5640	293	1.653	0.78
0543+2329	377	0.246	0.72	1844+1454	481	0.375	0.66
0601–0527	384	0.396	0.71	1900–2600	399	0.612	0.71
0614+2229	112	0.335	1.08	1907+4002	126	1.236	1.04
0629+2415	161	0.477	0.95	1913–0440	131	0.826	1.02
0630–2834	180	1.244	0.92	1915+1606	101	0.059	1.12
0653+8051	272	1.214	0.8	1919+0021	35	1.272	1.58
0659+1414	252	0.385	0.82	1921+2153	35	1.337	1.59
0700+6418	32	0.196	1.64	1932+1059	86	0.227	1.18
0738–4042	578	0.375	0.62	1935+1616	486	0.359	0.66
0742–2822	260	0.167	0.81	1946+1805	36	0.441	1.57
0754+3231	150	1.442	0.98	1948+3540	367	0.717	0.73
0814+7429	75	1.292	1.23	1954+2923	87	0.427	1.17
0820–1350	560	1.238	0.63	1955+5059	495	0.519	0.66
0823+0159	35	0.865	1.59	2018+2839	8	0.558	2.6
0826+2637	192	0.531	0.9	2022+2854	97	0.343	1.13
0835–4510	172	0.089	0.93	2022+5154	104	0.529	1.1
0837+0610	174	1.273	0.93	2046+1540	159	1.138	0.96
0908–1739	144	0.402	0.99	2046–0421	207	1.547	0.88
0922+0638	327	0.431	0.75	2048–1616	289	1.962	0.79
0943+1631	197	1.087	0.89	2055+3630	112	0.221	1.08
0944–1354	73	0.570	1.24	2113+2754	381	1.203	0.72
0946+0951	202	1.098	0.89	2116+1414	286	0.440	0.79
0953+0755	26	0.253	1.75	2149+6329	409	0.380	0.7
1115+5030	142	1.656	0.99	2157+4017	478	1.525	0.66
1136+1551	475	1.188	0.67	2219+4754	375	0.538	0.72
1239+2453	303	1.382	0.77	2225+6535	972	0.683	0.52
1321+8323	199	0.670	0.89	2235+1506	98	0.060	1.13
1430–6623	319	0.785	0.76	2305+3100	307	1.576	0.77
1453–6413	232	0.179	0.84	2308+5547	173	0.475	0.93
1456–6843	90	0.263	1.16	2313+4253	210	0.349	0.87
1509+5531	341	0.740	0.74	2354+6155	356	0.945	0.73

the pulsar, and accretion of this matter accelerates the pulsar to the millisecond level. The velocity of an MSP is about one-third that of a normal pulsar (Toscano et al. 1998). The parameters of MSPs are listed in Table 2, with the same format as Table 1. It is obvious that the initial periods of MSPs are close to their present periods; in most cases, the initial value is about 30 percent of the present value. For the fastest rotating pulsar, PSR J1937+21, the initial period is $0.777\,P$. Figure 2 shows the ratio of P_0/P as a function of P. The remarkable characteristic is that the ratio of P_0/P decreases with increasing P.

Table 2 Initial Period of Millisecond Pulsars

PSR J	V (km s^{-1})	P (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

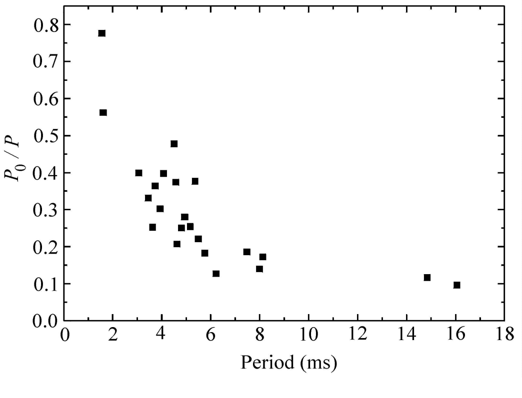

Fig. 2 Ratio of p_0/p as a function of p.

6 DISCUSSION AND CONCLUSIONS

The initial period can only be obtained for a few pulsars for which accurate ages and braking indices are known according to the model of magnetic dipole radiation. Furthermore, Eq. (1) is derived on the assumption that the magnetic momentum and the rotation inertia are constant. The measured braking index is not equal to 3: this indicates that these assumptions are questionable.

By using the off-center dipole emission theory, we have derived the initial periods of 94 normal pulsar and 23 MSPs. This is the first time that the initial periods for so many pulsars have been obtained. It is obvious that the initial periods are much shorter than those given by Eq. (1). Atoyan (1999) have derived a $3 \sim 5\,$ms initial period for the Crab pulsar. Our result in this paper is in the same direction, but is even shorter. It should be stressed that the initial periods here are lower limits.

We have noticed a remarkable difference between our result and the traditional value. In the off-center dipole radiation model, pulsars are accelerated to its last velocity in half a year. After this phase, the off-center dipole radiation continues but the acceleration can be neglected. Moreover, there are a few other factors to slow down the pulsar, one is gravitational waves from unstable r-mode oscillations (Anderson 1988), another is the disk-assisted spin down (Menou 2001).

The approach of the initial period and present period for MSPs is interesting. For most of the 23 MSPs, the initial periods are about 30 percent of their current periods. The suggestion of Camilo et al. (1994) that some MSPs were born with periods close to their current periods is consistent with the present finding.

Acknowledgements We wish to thank Dr. Xu Renxin for his helpful discussions. We also thank Mr. Xu Xuanbin, Mr. Ali Esamdin, Mr. Wang Hongguang and Ms. Zhou Aizhi for their help. This work is supported by the National Natural Science Foundation of China.

References

Anderson B., Lyne A. G., 1983, Nature, 303, 597
Anderson N., 1988, ApJ, 502, 708
Arras P., Lai D., 1999a, ApJ, 519, 745
Arras P., Lai D., 1999b, Phys. Rev. D., 60, 043001
Atoyan A. M., 1999, A&A, 346, L49
Bailes M., 1989, ApJ, 342, 917
Bhattacharya D., Wijers R. A. M. J., Hartman J. W., Verbunt F., 1992, A&A, 254, 198
Blaauw A., 1961, BAN, 15, 265B
Blandford R. D., Romani R. W., 1988, MNRAS, 234P, 57B
Blandford R. D., Applegate J. H., Hernquist L., 1983, MNRAS, 204, 1025B
Burrows A., Hayes J., 1996, PhysRev. Lett., 76, 352
Burrows A., Hayes J., Frexell B. A., 1995, ApJ, 450, 830
Chatterjee S., 2001, http://www.astro.cornell.edu/~shami/psrvlb/parallax.html.
Cordes J. M., Chernoff D. F., 1998, ApJ, 505, 315
Cordes J. M., Romani R. W., Lundgren S. C., 1993, Nature, 362, 133
Deshpande A. A., Ramachandran R., Radhakrishnan V., A&A, 351, 195

Edwards R. T., van Straten W., Bailey M., 2001, ApJ, 560, 365

Fomalont E. B., Goss W. M., Lyne A. G., Manchester R. N., Justtanont K., 1992, MNRAS, 258, 497F

Fomalont E. B., Goss W. M., Manchester R. N., Lyne A. G., 1997, MNRAS, 286, 81F

Friedman J. L., Parker L., Ipser J. R., 1984, Nature, 312, 255

Ganesler B. M., Frail D. A., 2000, Nature, 406, 158

Gutt J. R., Gunn J. E., Ostriker J. P., 1970, ApJ, 160, L91

Harrison P. A., Lyne A. G., Anderson B., 1993, MNRAS, 261, 113

Herant M., Benz W., Hix W. R., Fryer C. C., Stirling A., 1994, ApJ, 435, 339

Kaspi V. M., Roberts M. E., Vasisht G., Gotthelf E. V., Pivovaroff M., Kawai N., 2001, ApJ, 560, 371

Lai D., Chernoff D. F., Cordes J. M., 2001, ApJ, 549, 1111

Legge D., 2000, Astrometry of sothern Pulsars, ASP Conf. Ser. 202 IAU Colloq. 177: Pulsar Astronomy – 2000 and Beyond, 141

Lyne A. G., Lorimer D. R., 1994, Nature, 369, 127

Lyne A. G., Pritchard R. S., Graham-Smith F., Camilo F., 1996, Nature, 381, 497

Manchester R. N., Taylor J. H., Van Y. -Y., 1974, ApJ, 189, L119

Marshall F. E., Gotthelf E. V., Zhang W. et al., 1998, ApJ, 499, L179

Menou K., Perna R., Hernquist L., 2001, ApJ, 554, L63

Migliazzo J. M., Gaensler B. M., Backer D. C. et al., 2002, ApJ, 567L, 141M

Moffett D. A., Hankins T. H., 1999, ApJ, 522, 1046

Narayan R., Ostriker J. P., 1990, ApJ, 319, 162

Pavlov G. G., Kargaltsev O. Y., Sanwal D., Garmire G. P., 2001, ApJ, 554, L189

Pskovskii Iu. P., Dorofeev O. F., Nature, 340, 701

Qiao G. J., Wu X. J., Zhang H., Xia X. Y. et al., 1985, Science Bulietin, 8, 1062

Radhakrishnan V., 1992, In: van den heuvel E. P. J., Rappaport S. A., eds., X-ray Binaries and Recycled Pulsars, Dordrecht: Kluwer, p.445

Ryba M. F., Taylor J. H., 1991, ApJ, 196, 51

Sedrakian A., Wasserman I., Cordes J. M., 1999, ApJ, 524, 341

Shklovskii I. S., 1970, Sov. Astron., 13, 526

Stair I. H., Lyne A. G., Shemar S. L., 2000, Nature, 406, 484

Stinebring D. R., Sinirnova T. V., Hankins T. H., 2000, ApJ, 539, 300

Taylor J. H., Manchester R. N., Lyne A. G., 1993, ApJS, 88, 529

Toscano M., Sandhu J. S., Bailes M. et al., 1999, MNRAS, 307, 925

Wang N., Wu X. J., Manchester R. N. et al., 2001, Chin. J. Astron. Astrophys. (ChJAA), 1(5), 421

Weisberg J. M., Romani R., Taylor J. H., 1989, ApJ, 347, 1030

Weisskopf M. C., Hester J. J., Tennant A. F. et al., 2000, ApJ, 536, L81

Xu R. X., Wang H. G., Qiao G. J., 2002, Chin. J. Astron. Astrophys. (ChJAA), 2(6), 533

Zhang W., Marshall F. E., Gotthelf E. V., Middleditch J., Wang Q. D., 2001, ApJ, 554, L177