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Circular Polarization in Pulsar Integrated Profiles: Updates *

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Abstract We update the systematic studies of circular polarization in integrated pulse profiles by Han et al. Data of circular polarization profiles are compiled. Sense reversals can occur in core or cone components, or near the intersection between components. The correlation between the sense of circular polarization and the sense of position angle variation for conal-double pulsars is confirmed with a much large database. Circular polarization of some pulsars has clear changes with frequency. Circular polarization of millisecond pulsars is marginally different from that of normal pulsars.

Key words: polarization — pulsars: general

1 INTRODUCTION

Polarization properties of pulsars are very important for the understanding of the geometry and emission mechanism of pulsars. Generally, the degree of circular polarization is low. Many pulsars show sense reversal in their circular polarization near the middle of the pulse. The sense reversals sometimes are associated with the orthogonal polarization modes (Cordes et al. 1978; Stinebring et al. 1984a). In some pulsars, the circular polarization keeps the same sense through the whole profile. Two obvious types of circular polarization are identified by Radhakrishnan & Rankin (1990), namely: *antisymmetric*, where the circular polarization changes sense near the center of the profile, and *symmetric*, where the circular polarization remains the same sense through the whole profile. Han et al. (1998) collected the published polarization profiles and reviewed the characteristics of circular polarization in pulsar integrated profiles, discovered a correlation between the sense of circular polarization and the sense of position angle (PA) variation for conal-double pulsars, and rebutted the correlation between the sense reversal of circular polarization near the core components and the sense of PA.

There are two possible origins of circular polarization of pulsars: either intrinsic to the emission properties and dependent on the emission mechanism, or generated by propagation effects. For example, Melrose & Luo (2004) discussed possible circular polarization induced by intrinsically relativistic effects of pulsar plasma. Melrose (2003) reviewed the properties of intrinsic circular polarization and circular polarization due to cyclotron absorption, and presented a plausible explanation of circular polarization in terms of propagation effects in an inhomogeneous birefringent plasma. Lyubarskii & Petrova (1999) considered that the rotation of the magnetosphere gives rise to wave mode coupling in the polarization-limiting region, which can result in circular polarization in linearly polarized normal waves.

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A large sample of normal pulsars and millisecond pulsars has been observed for polarization (Gould & Lyne 1998; Stairs et al. 1999; Weisberg et al. 1999; Weisberg et al. 2004; Han et al. 2006), especially at multiple frequencies. The data have increased by a factor of about three over that in Han et al. (1998). So, it is the time to update the database of pulsar circular polarization and recheck the conclusions of that paper.

2 DATASET

Polarization profiles of pulsars are collected and cataloged if the circular polarization has a good signal-to-noise ratio. Circular polarization is defined observationally by the Stokes parameter, $V = I_L - I_R$. The rotational sense of V, the percentage ($=\langle V\rangle/S$, where S is the mean total flux density), and absolute circular polarization percentage, $\langle|V|\rangle/S$, the variation of PA, and observation frequency are all included in Table 1 (This is only part of Table 1. For the full Table 1 see http://www.chjaa.org/2006v1n2/ for electronic version), which has the same format as table A1 in Han et al. (1998).

Table 1 A Summary of Pulsar Circular Polarization Observations

PSR J	PSR B	V	$\langle\|V\|\rangle/S$ (%)	$\langle V\rangle/S$ (%)	σ (%)	PA	Freq. (MHz)	Ref.	Comments
0030+0454		−−				dec	433	L00	MSP. −− for main comp
0034−0534		−−	18			xx	410	S99	PA swing not clear
0034−0721	0031−07	+	10	5	1	dec	234	G98	
		+				dec	268	R83	$+V$ in 2nd half
		+				dec	328	S05	$+V$ in 2nd half
		−	6	−6	0	inc	410	G98	$-V$ in 1st half
		+	5	4	0	i+d	606	G98	$+V$ in 2nd half
		+				dec	4850	S05	$+V$ in 2nd half
0040+5716	0037+56	−	18	−17	1	inc	610	G98	s/n good
0045−7319		−	27	−17	7	xx	661	C01	strong cp
0048+3412	0045+33	−				dec	430	W04	PA not very clear. low linear polarization

3 MAIN PROPERTIES OF CIRCULAR POLARIZATION

3.1 Sense Reversal of Circular Polarization

3.1.1 Sense reversals associated with core components

Using a sample of 25 pulsars, Radhakrishnan & Rankin (1990) found that change of circular polarization from left-hand (positive) to right-hand (negative) is associated with decreasing PA, and that from right-hand to left-hand is associated with increasing PA. Gould (1994) and Han et al. (1998) found many contrary examples, which leads Han et al. (1998) to conclude that no correlation exists between the sense of the sign change of circular polarization and the sense of variation of PA.

Here we use a very large sample of pulsar data and confirm the conclusion of non-correlation. Table 2 lists all pulsars with sense reversal of circular polarization in the core component, and 19 pulsars in the first and fourth part of Table 2 support the existence of the correlation, but 20 pulsars in the second and third part do not.

3.1.2 Sense reversals outside core

Many sense reversals of circular polarization are detected outside of the center region of the profile, thus not associated with core components but with cone components or near the conjunction of components. Table 3 lists such pulsars with sense reversals in the other part of the pulse profile.

Table 2 Sense Reversals of Circular Polarization Associated with Core Components

PSR Name	$V = LH - RH$	PA	Freq. (MHz)	Ref.
J0454+5543	+/−	dec	610	G98
J0809−4753	+/−	dec	1335	H06
J1001−5507[a]	+/−	dec	1351	H06
J1239+2453	+/−	dec	1418	W99
J1509+5531	+/−	dec	610	G98
J1534−5334	+/−	dec	1612	Ma80
J1740+1311	+/−	dec	1418	W99
J1801−0357[b]	+/−	dec	661	M98
J1823+0550	+/−	dec	1408	G98
J1900−2600	+/−	dec	1408	G98
J1901+0331	+/−	dec	1418	W99
J1903−0632	+/−	dec	610	G98
J1946−2913	+/−	dec	1327	H06
J2048−1616	+/−	dec	1420	LM88
J2113+4644	+/−	dec	610	G98
J0826+2637m	+/−	inc	1400	R89
J1512−5759	+/−	inc	1319	H06
J1600−3053[c]	+/−	inc	1373	O04
J1604−4909	+/−	inc	658	M98
J1733−2228[b]	+/−	inc	610	G98
J1910−0309	+/−	inc	1408	G98
J1926+0431	+/−	inc	1418	W99
J2004+3137	+/−	inc	1400	R89
J2006−0807	+/−	inc	1408	G98
J0332+5434	−/+	dec	1408	G98
J0437−4715	−/+	dec	1512	N97
J0944−1354	−/+	dec	409	LM88
J1326−5859	−/+	dec	955	v97
J1456−6843	−/+	dec	649	Mc78
J1527−5552	−/+	dec	658	M98
J1537+1155	−/+	dec	430	A96
J1544−5308	−/+	dec	658	M98
J1752−2806	−/+	dec	1408	G98
J1852−2610	−/+	dec	434	M98
J1909+0254[b]	−/+	dec	610	G98
J0452−1759	−/+	inc	408	LM88
J1703−3241	−/+	inc	950	v97
J2144−3933	−/+	inc	659	M98
J2325+6316[c]	−/+	inc	1642	G98

[a] New high resolution observation show decreasing PA. Old data are confused by orthogonal polarization modes.
[b] PA not clear.
[c] Not so sure if sense reversal happens in core.

Table 3 Sense Reversals not Associated with Core Components

PSR Name	$V = LH - RH$	PA	Freq. (MHz)	Ref.	Comments
J1651−4246	+/−	dec	1349	H06	intersection between two comp
J1807−0847	+/−	dec	1408	G98	cone
J1857+0943m	+/−	dec	1400	S86	intersection between two comp
J1907+4002	+/−	dec	1408	G98	intersection between two comp?
J2324−6054	+/−	dec	1335	H06	intersection between two comp
J0152−1637	+/−	inc	660	Q95	intersection between two comp
J0612+3721	+/−	inc	610	G98	associated with orthogonal polarization modes
J0653+8051	+/−	inc	610	G98	cone?
J0738−4042	+/−	inc	1351	H06	associated with orthogonal polarization modes
J0837+0610	+/−	inc	800	S84b	leading cone
J1913−0440	+/−	inc	408	G98	associated with orthogonal polarization modes
J2022+2854	+/−	inc	800	S84b	leading cone
J2053−7200	+/−	inc	658	M98	intersection between two comp
	−/+	inc	1440	Q95	intersection between two comp
J2145−0750	+/−	inc	610	S99	cone
J2326+6113	+/−	inc	1408	G98	intersection between two comp?
J1708−3426	+/−	??	1329	H06	intersection between two comp
J0133−6957	−/+	dec	658	M98	intersection between two comp
J1041−1942	−/+	dec	1642	G98	leading cone
J1045−4509	−/+	dec	1373	O04	cone?
J1559−4438	−/+	dec	1490	M98	intersection between trailing two comp
J1614+0737	−/+	dec	1418	W99	intersection between two comp
J1705−1906m	−/+	dec	1642	G98	intersection between two comp
J1751−4657	−/+	dec	434	M98	leading cone
J1916+0951	−/+	dec	610	G98	leading cone
J1935+1616	−/+	dec	1408	G98	intersection between two comp
J0255−5304	−/+	inc	1359	H06	second cone
J0502+4654	−/+	inc	1408	G98	intersection between two comp
J0601−0527	−/+	inc	408	G98	intersection between two comp
J0941−5244	−/+	inc	1319	H06	intersection between two comp
J1224−6407	−/+	inc	1319	H06	intersection between two leading comp
J1328−4357	−/+	inc	435	M98	intersection between two leading comp
J1921+2153	−/+	inc	1418	W99	cone
J1602−5100	−/+	??	950	v97	intersection between two leading comp

3.1.3 Sense reversals associated with orthogonal polarization modes

We checked possible association of sense reversal of circular polarization with orthogonal polarization modes of the polarization angle. Among 81 pulsars with sense reversals in V with clear PA variation curves, about 31 show the association. For example, the PA jumps about 90° seen in PSRs J1900−2600, J0601−0527 and J0437−4715 at almost all the observed frequencies (Manchester et al. 1998; Gould & Lyne 1998; Navarro et al. 1997), near the phase of a sense transition of circular polarization. A few pulsars show two sense reversals across the profile, as shown in Figure 1 for PSR J2037+1942 which has sense reversals associated with the peaks of two components. The orthogonal polarization modes occur in the first component (Weisberg et al. 1999). The polarization curve thus does not have a good $S-$shape.

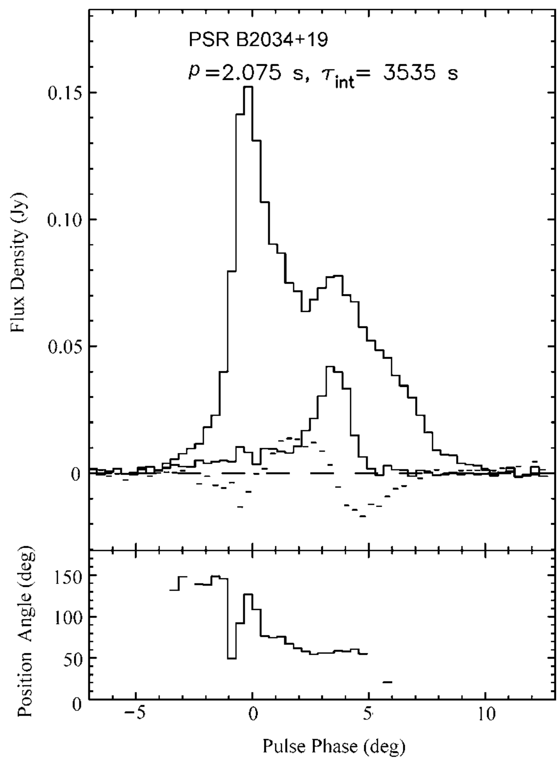

Fig. 1 Polarization profile of PSR J2037+1942 at 1418 MHz (from Weisberg et al. 1999). The total (higher full line), linear polarized (lower full line) and circular polarized (dotted line) flux densities are displayed in the upper panel. The lower panel shows the PA curve.

3.2 Circular Polarization of Conal-double Pulsars

Using the polarization data of a sample of 20 conal-double pulsars available at that time, Han et al. (1998) found a strong correlation between the sense of PA sweep and the sense of circular polarization for conal-double pulsars, namely, a decrease of PA accompanies with left-hand circular polarization of conal components, and an increase of PA with the right-hand. Occasionally, sense reversal is observed in one cone component of profiles.

Table 4 Conal-double Pulsars with Significant Circular Polarization

PSR Name	PA	Sign of V Comp 1	Sign of V Comp 2	Ref.
J0151−0635	inc	−	−	LM88, G98
J0528+2200	inc	−	−	S84a, R83
J0653+8051	inc	+/−	−	G98
J0754+3231	inc	−	−	R89, G98
J0820−1350	inc	−	−	v97, Q95, B87
J0837+0610	inc	−	−	Mc78, S84a, G98
		+/−	−	S84b
J0959−4809	inc	−	−	H06
J1015−5719	inc	−	−	H06
J1110−5637	inc	·	−	H06
J1136+1551	inc	−	−	Mc78, S84a, G98
J1137−6700	inc	−	−	H06
J1159−7910?	inc	·	−	H06
J1420−6048	inc	−	−	R01
J1906+0641	inc	−	·	W99
J1915+1606	inc	−/+	−	C90
J1921+2153	inc	−/+	−	W99
J1954+2923	inc	−	−	G98
J2022+2854	inc	−	−	C78, S84a, W99
J2046+1540	inc	−	−	G98
J2053−7200	inc	+/−	−	Q95, M98
		−/+	−	Q95, H06
J2124+1407	inc	−	−	W04
J0055+5117	dec	+	+	G98
J0304+1932	dec	+	+	R83, R89, W99
J0631+1036	dec	+	+	Z96
J1041−1942	dec	−/+	+	LM88, G98
J1123−4844	dec	+	+	M98
J1302−6350	dec	+	·	MJ95
J1345−6115	dec	+	·	H06
J1527−3931	dec	+	+	M98
J1731−4744	dec	+	·	H77, Mc78, v97
J1751−4657	dec	−/+	+	M98
J1803−2137	dec	+	+	G98
J1826−1344	dec	+	+	G98
J2055+2209	dec	+	+	G98
J2324−6054	dec	+	·	Q95
J2346−0609	dec	·	+	M98

?: Not so sure for conal-double pulsar.

Now, using a larger sample of 36 pulsars, the correlation is solidly confirmed. Table 4 lists all conal-double pulsars with good measurements of circular polarization and PA.

We also checked if there is any correlation between the polarization percentage and the maximum sweep rate of PA. Ideally, the PA should follow the S-shaped curve across the pulse profile as described by the rotating vector model (Radhakrishnan & Cooke 1969). The maximum rate of polarization sweep, which occurs when the line of sight passes closest to the magnetic axis, is given by $\left(\frac{d\psi}{d\phi}\right)_m = \frac{\sin\alpha}{\sin\beta}$, where ψ is the PA, ϕ is the longitude, α is the inclination of the magnetic axis to the rotation axis, and β is the impact parameter given by $\beta = \zeta - \alpha$, where ζ is the inclination of the observer direction to the rotation axis. The value of $\left|\frac{d\psi}{d\phi}\right|_m$ very sensitively depends on $|\beta|$. Smaller $|\beta|$, i.e. the magnetic axis closer to the observer direction, gives a larger $\left|\frac{d\psi}{d\phi}\right|_m$. Figure 2 shows the relationship between $\langle V\rangle/S$ and $\left(\frac{d\psi}{d\phi}\right)_m$ at 1400 MHz for conal-double pulsars. There are only 27 pulsars in Figure 2 because some pulsars have not been observed near 1400 MHz or the observed PA does not have a good enough S-shaped curve to estimate $\left|\frac{d\psi}{d\phi}\right|_m$. Pulsars are located

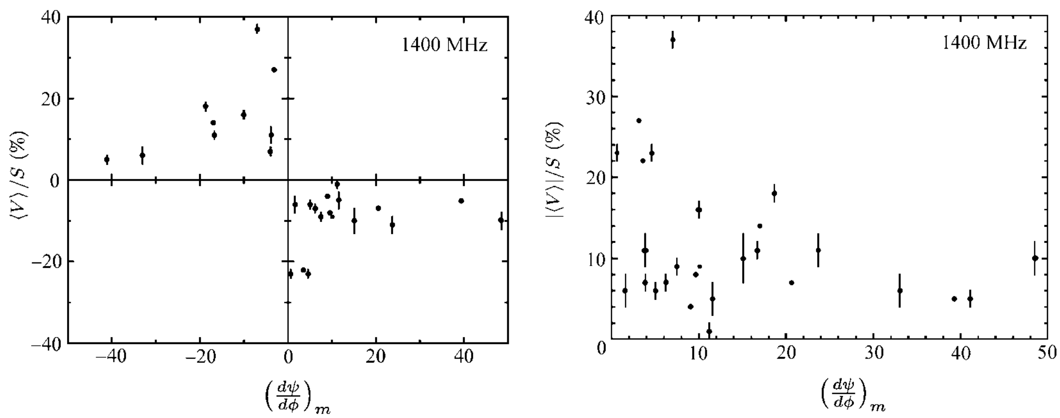

Fig. 2 The maximum polarization sweep rate $\left(\frac{d\psi}{d\phi}\right)_m$ is related to the fractional circular polarization $\langle V\rangle/S$ at 1400 MHz. The data of $\left(\frac{d\psi}{d\phi}\right)_m$ were taken from Gould (1994), Han et al. (2006), or estimated by ourselves.

in the second and forth quadrants in Figure 2, which confirms the correlation between the sign of PA swing and the sense of V. Furthermore, we noticed that $|\langle V\rangle|/S$ tends to decrease with $\left|\frac{d\psi}{d\phi}\right|_m$.

3.3 Circular Polarization with Frequency

The circular polarization of some pulsars clearly changes with frequency. von Hoensbroech & Lesch (1999) showed three pulsars with a trend of increasing circular polarization with frequency, which was interpreted in terms of propagating natural wave modes in pulsar magnetosphere.

The variation of degree of circular polarization with frequency is very different from pulsar to pulsar. Figure 3 shows eight good examples: Four of the pulsars show their circular polarizations increasing with frequency, but the other four in the latter part of the figure show a decrease.

In some pulsars, the sign of sense reversal clearly changes with frequency. PSR J2053−7200 shows a sense reversal near the intersection of two components from the left-hand to right-hand at low frequencies (Qiao et al. 1995; Manchester et al. 1998; van Ommen et al. 1997), but from the right-hand to left-hand at high frequencies (Qiao et al. 1995; Han et al. 2006).

3.4 Circular Polarization in Normal Pulsars and Millisecond Pulsars

Compared to normal pulsars, millisecond pulsars have weaker surface magnetic fields, wider profiles, and a different profile dependence on frequency (Kramer et al. 1998; Kramer et al. 1999). Though their PA variations are often more complicated, most of them appear to follow the rotating vector model. The basic radio emission mechanism may be similar for millisecond pulsars and normal pulsars. Xilouris et al. (1998) found that the fractional absolute circular polarization is higher for millisecond pulsars than for normal pulsars, based on observations at 1410 MHz.

Here we compiled a sample of millisecond pulsars observed near 1400 MHz as listed in Table 5 (Stairs et al. 1999; Manchester & Han 2004; Ord et al. 2004) and compared their circular polarization with that of normal pulsars. The distributions of degree of circular polarization of millisecond pulsars and normal pulsars are marginally different, as shown in Figure 4. The Kolmogorov-Smirnov test returned a probability of 16.49% for the two populations being from the same distribution.

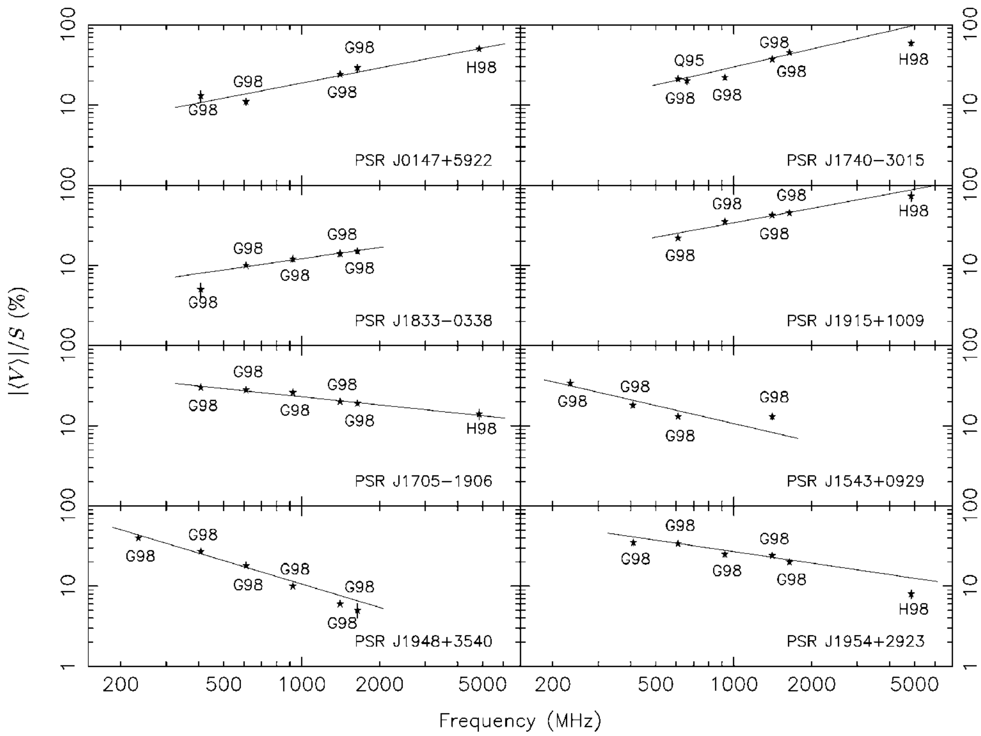

Fig. 3 Eight pulsars with clear variation of circular polarization with frequency.

Table 5 Circular Polarization of Millisecond Pulsars Near 1400 MHz

PSR Name	Period (ms)	$\langle\lvert V\rvert\rangle/S$ (%)	$\langle V\rangle/S$ (%)	Err. (%)	Freq. (MHz)	Ref.
J0437−4715	5.76	11	−5	1	1512	N97
J0711−6830	5.49	16			1405	O04
J1022+1001	16.45	10			1405	O04
J1045−4509	7.47	14			1373	O04
J1600−3053	3.60	3			1373	O04
J1603−7202	14.84	28			1405	O04
J1623−2631	11.08	18	1	3	1331	MH04
J1629−6902	6.00	14			1373	O04
J1643−1224	4.62	11	−1	1	1331	MH04
J1713+0747	4.57	3			1373	O04
J1730−2304	8.12	17			1405	O04
J1748−2446	11.56	14			1414	S99
J1757−5322	8.86	19			1373	O04
J1804−0735	23.10	13	−12	1	1408	G98
J1857+0943	5.36	6			1373	O04
J1909−3744	2.94	14			1373	O04
J1911−1114	3.63	17			1373	O04
J1915+1606	59.03	17	−10	3	1408	G98
J1933−6210	3.54	6			1373	O04
J1939+2134	1.56	3			1414	S99
J2051−0827	4.51	10			1341	O04
J2124−3358	4.93	6	−1	1	1327	MH04
J2129−5721	3.73	30			1373	O04
J2145−0750	16.05	5			1373	O04

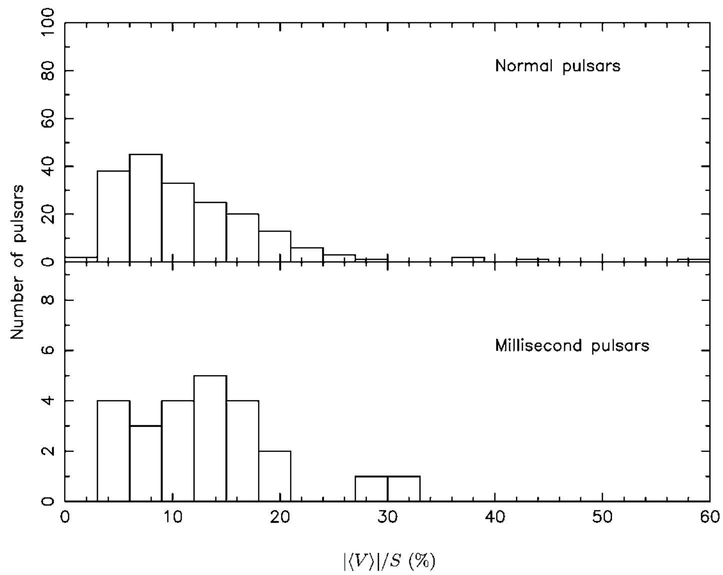

Fig. 4 Comparison of fractional absolute circular polarization of normal pulsars and millisecond pulsars.

4 DISCUSSION

Circular polarization can be generated by several emission mechanisms including curvature emission, coherent emission and cyclotron absorption. Michel (1987) first noted that curvature emission can explain the sense reversal of the circular polarization. Following this model, Gil & Snakowski (1990) re-examined curvature radiation and demonstrated that circular polarization could have a sense reversal near pulse center. Xu et al. (2000) considered coherent emission of a bunch of electrons with inverse Compton scattering, and found that circular polarization can be produced at low emission altitudes. On the other hand, cyclotron absorption may also produce circular polarization (Melrose 2003).

Propagation effects can induce circular polarization or at least influence circular polarization. There are two kinds of propagation effect. One is in the pulsar magnetosphere and the other in interstellar medium (ISM). Petrova & Lyubarskii (2000) investigated refraction and polarization transferring in an ultra-relativistic highly magnetized pulsar plasma. They found that circular polarization arises out of rotation of the magnetosphere. Two main types of circular polarization defined by Radhakrishnan & Rankin (1990) can be explained by refraction in the plasma with non-axisymmetric density distribution and by magnetosphere rotation. Petrova (2001) also found that the change in the sense of circular polarization can occur near the orthogonal transitions or from non-orthogonality of the observed modes.

Macquart & Melrose (2000) discussed a scintillation-induced circular polarization in the interstellar medium due to rotation measure gradient. The degree of circular polarization induced by diffractive scintillation at lower frequency is more significant. We calculated this effect due to rotation measure gradient (van Ommen et al. 1997; Han et al. 1999; Weisberg et al. 2004) and found this effect is very small (less than a few percent) except for a few pulsars at low frequency.

The correlation between the sense of PA variation and the sense of V in conal-double pulsars may give some constraints to the geometry and mechanism of pulsar emission. Qiao et al. (2004) proposed the inner annular gap (IAG) to explain the emission from pulsars. For neutron stars, an IAG can be formed only for a pulsar ($\boldsymbol{\Omega} \cdot \boldsymbol{B} < \mathbf{0}$), not for an antipulsar ($\boldsymbol{\Omega} \cdot \boldsymbol{B} > \mathbf{0}$), and the beam is asymmetric in shape, much larger toward the equator. According to this model, as Figure 5 shows, conal-double pulses are more likely generated in the region close to equator of the pulsar

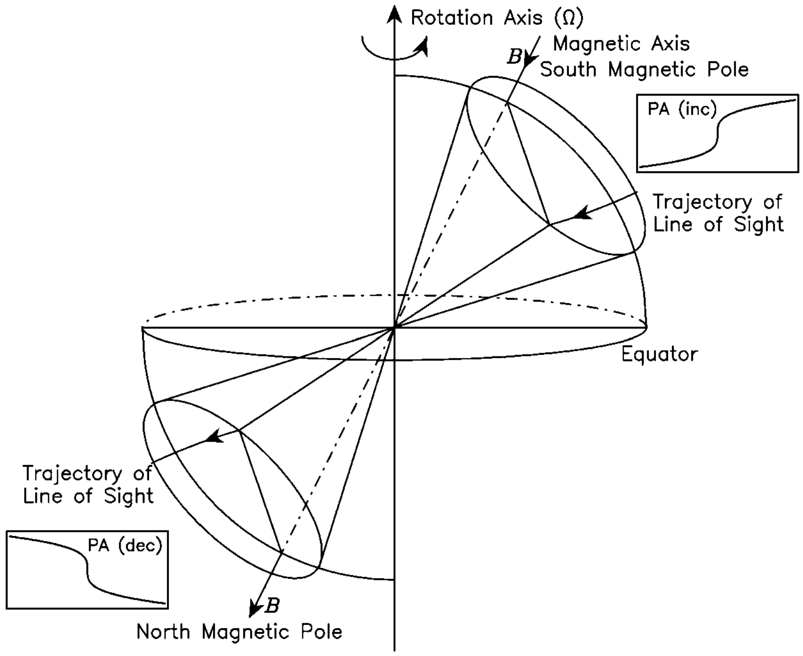

Fig. 5 IAG geometry of a pulsar, the beam geometry for the inner annular gap model. The PA decreases or increases with the pulse longitude as the line of sight cuts the beam between the equator and the Northern or Southern magnetic pole.

($\boldsymbol{\Omega} \cdot \boldsymbol{B} < \mathbf{0}$). We also know that the PA decreases or increases with the pulse longitude when the line of sight cuts the beam between the equator and the Northern or Southern magnetic pole. Based on the observed correlation in conal-double pulsars and the properties of IAG model, the conal emission of pulsars in the first part of Table 4 is produced from the South magnetic pole and has right-hand circular polarizations, whereas the emission of pulsars in the second part of Table 4 is from the North magnetic pole and has left-hand circular polarization.

5 CONCLUSIONS

Circular polarization in pulsars shows diverse patterns. Though sense reversal of circular polarization often occurs in the core components, it can also happen in the cone components or near the intersection between components. We confirm the correlation between the sense of circular polarization and the sense of position angle sweep for conal-double pulsars. Circular polarization of some pulsars get stronger with frequency, but others get weaker. The senses of circular polarization of conal-double pulsars may be related to the different magnetic poles.

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