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Depolarization and position angle jumps due to relative longitude shift of pulsar beams

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Abstract. Pulsar radio emission is generally found to be linearly polarized over all longitudes of profiles, some times as high as up to 100%. The position angle sweep is in an 'S' shape, which can be well understood within the rotating vector model (Radhakrishnan & Cooke 1969). However, depolarization and position angle jumping are often found in the integrated profiles of some pulsars. In this paper, we investigate the effect on polarization behaviour due to relative phase shift between pulsar beam components caused by retardation effect, considering that the core and conal emission components are radiated from different heights. We conclude that the phase shift of beam centers of the different components could cause the depolarization and position angle jump(s) in integrated profiles.

Key words: pulsars: general – polarization

1. Introduction

Polarization observations of pulsars provide much information about the physics of emission region. It is widely accepted that pulsar emission comes from the magnetic poles of neutron stars, and the behaviour of the position angle of linear polarization can be well interpreted by the rotating vector model (Radhakrishnan & Cooke 1969). However, the pulsar integrated profiles are diverse on the percentage of linear polarization from one pulsar to another and even from longitude to longitude of a given profile. Sometimes the linear polarization becomes to zero at a given longitude, so that one can see, almost certainly, that the smoothly-changing position-angle curve will suddenly jump almost 90^o at this longitude. One example is shown in Fig. 1. Similar phenomena can be found from polarization observations of PSR B1857-26 at 631 MHz, B0450-18 at 408MHz and B0450+55 at 409MHz (Lyne & Manchester 1988), B1937+21 at 1418MHz or higher frequencies (Thorsett & Stinebring 1990), B1929+10 at 430MHz and 1665MHz (Phillips 1990), B1855+09 at 1400MHz (Segelstein et al. 1986), B1839+09 at 1400MHz (Rankin, Stinebring & Weisberg 1989), B1601-52 at 660MHz (Qiao et al. 1995), etc.

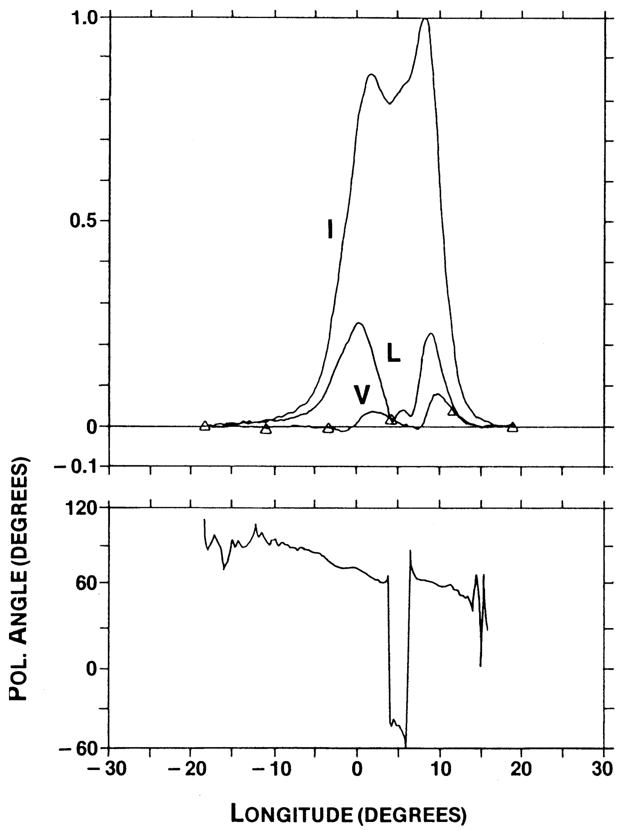

Fig. 1. One example of the depolarization which results in polarization position-angle jumps. The polarization observation of PSR B1604−00 was done by Rankin (1988) at 430MHz.

Nonmonotonic and discontinuous rotation of polarization position angle observed from some pulsars is generally attributed to the occurrence of orthogonal or non-orthogonal modes of polarization in subpulses (Manchester, Taylor &

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Huguenin 1975; Cordes, Rankin & Backer 1978, Stinebring 1984a,b; Gil & Lyne 1995; Gil et al. 1992). Shier & Michel (1992) explain the discontinuities of position angle and multicomponentedness of pulsar profiles by involving the second emission hollow cone with orthogonal polarization. Certainly, the flips of the orthogonal or non-orthogonal emission modes of single-pulse emission can result in depolarization and position-angle discontinuities. However, it would be difficult to account the seperated polarization modes by Rankin (1988) for PSR B1604-00, which show that the position-angle curves of the core and conal components are seperated several tens degrees and that they sweep in different 'S' shapes. Similar phenomena can also be found from the integrated profile of PSR B0823+26 (Blaskiewicz, Cordes & Wasserman 1991) and its seperated polarization modes (Rankin & Rathnasree 1995).

In this paper, we investigate retardation effects as they effect the linearly polarized pulsar beam components of integrated pulse profiles, on the assumption that the core and conal beam components are radiated incoherently from different heights. We found that the phase shifts of beam centers of the different components could also cause the depolarization and position-angle jump(s) in integrated profiles.

2. Aberration and retardation effects

With polarization information, the core and conal emission beams have been identified from the integrated pulse profiles by Rankin (1983), and later confirmed by Lyne and Manchester (1988). After studying a large body of observational data, Rankin (1993) concludes that the core component is emitted at lower height than the cone. Cordes, Wasserman & Blaskiewicz (1990) had the same suggestion for the emission beam of PSR B1913+16 from the detailed analyses of observational data. On theoretical aspects, Qiao et al. (1992) calculate the emission heights of pulsar emission beam components in the inverse Compton scattering model which Qiao (1988 a,b, 1992) and Qiao & Lin (1996) suggested for radio pulsars, and found that the emission region corresponding to the core component is nearest to neutron star surface, while that of inner cone is farther, and that of outer cone is farthest. As long as the core and conal emission components are emitted from different heights, aberration and retardation effects should move the apparent position on the celestial sphere of the core to a later longitude with respect to the position of the center of the cone (see Fig. 2), and could even move it outside the cone (McCulloch 1992). One direct example for such a beam phase shift is found by McKinnon & Hankins (1993) from the less intense pulse profile of PSR B0329+54.

Suppose that the core and cone components are emitted from the heights of h_1 and h_2 (here $h_1 < h_2$), respectively. The polarization position angle behaviuor follows the rotating vector model. At a logitude ϕ, the position angle of the ith component is (ref. Fig. 2)

$$\psi_i = \tan^{-1}[\frac{\sin\alpha\sin(\phi-\phi_i)}{\sin(\alpha+\beta)\cos\alpha - \cos(\alpha+\beta)\sin\alpha\cos(\phi-\phi_i)}]. \quad (1)$$

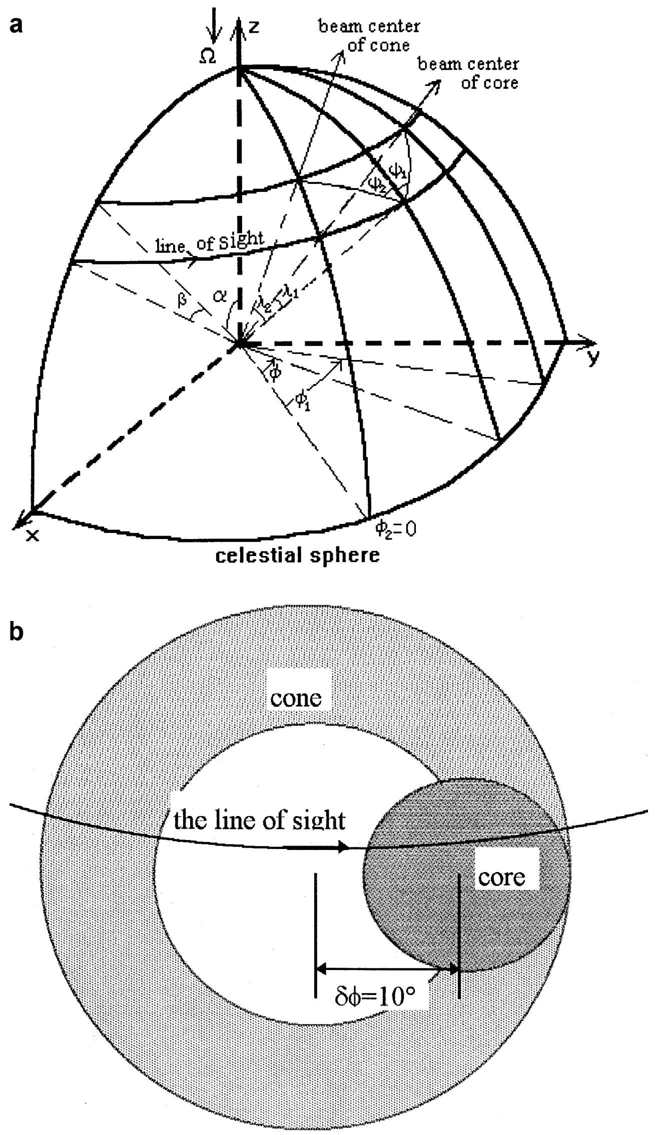

Fig. 2. **a** The geometry of pulsar emission beams. The parameters used in the text are defined in the figure. **b** The two dimensional beam on the celestial sphere. The core is coming later so that the beam center shifts towards a later longitude.

Here, i = 1 denotes the core and i = 2 the cone. The phase shift $\delta\phi$ between the beam centers of the core and cone components on the celestial sphere, due to aberration and retardation effects, will be

$$\delta\phi = \frac{\Delta h/c}{P}\cdot 360^o \quad (2)$$

where c is the speed of the light, P the rotation period of a pulsar, $\delta\phi = \phi_1 - \phi_2$ and $\Delta h = h_2 - h_1$. For example, if Δh = 100km, P = 0.01s, then, accoding to Eq. (2), $\delta\phi$ = 12^o; if Δh = 1000km, P = 0.2s, then, accoding to Eq. (2), $\delta\phi$ = 6^o.

Note that the superposition of emission from the two beam components is not the sum of electromagnetic wave vectors, but of the Stokes parameters. In this paper, we will explore the case of completely linear polarization and will not consider any circular polarization. The Stokes parameters of the polarized emission of the ith component are

$$\begin{cases} I_i &= I_i^{unp} + L_i = L_i \\ Q_i &= L_i \cos(2\psi_i) \\ U_i &= L_i \sin(2\psi_i) \\ V_i &= 0 \end{cases} \quad (3)$$

Here, I_i^{unp}, L_i are the intensities of unpolarized and polarized contributions, respectively. If the emissions from these components are incoherent, the observed total Stokes parameters are the summation of each parameter

$$\begin{cases} I &= \Sigma I_i &= I^{unp} + L \\ Q &= \Sigma Q_i &= L\cos(2\psi) \\ U &= \Sigma U_i &= L \sin(2\psi), \end{cases} \quad (4)$$

where L is the total linearly polarized intensity, ψ the observed position angle of the integrated profile, $L = (Q^2 + U^2)^{1/2}$ and $\psi = 1/2 \arctan(U/Q)$. As we will see from the simulations in the next section, the superposed emission will be depolarized so that I^{unp} is not equal to zero sometimes, depending on the difference of position angles and intensities between the two superposed beam components as well.

It is possible that there are some points where $L = 0$. We define these points as "singular points". *When the line of sight travels across such a point, the position angle ψ will generally have a discontinuity, or say, a sudden jump of* 90^{o}[1].

For the superposition of two emission beams, two conditions must be satisfied to get a singular point:

$$\begin{cases} \psi_1 - \psi_2 &= \pm\pi/2 \\ L_1 &= L_2 \end{cases} \quad (6)$$

3. Simulations

Basic assumptions used for our simulation are as follows:
(1). Different beam components are emitted from different heights;
(2). Emission from one beam component is incoherent to that from another;
(3). The position angle variation of each beam component can be described by the rotating vector model (Radhakrishnan & Cooke 1969);
(4). The core component has a Gaussian shape,

$$L_1 = A_1 \exp(-\frac{\lambda_1^2}{2\sigma_1^2}). \quad (7)$$

Here $\lambda_1 = \cos^{-1}[\cos\alpha\cos(\alpha+\beta) + \sin\alpha\sin(\alpha+\beta)\cos(\phi-\phi_i)]$ is the angular distance between the observed point and the beam center, σ_1 the width of the Gaussian, A_1 is the intensity at the beam center. The conal emission is in the form of a torus with a cross-section of another Gaussian; the width σ_2 of the cross section of the conal torus is taken to be $0.8\sigma_1$.

[1] One may easily reach this conclusion by inspecting the variation of Stokes parameters in the vicinity of the point. As long as $\frac{dQ}{d\phi} = \Sigma\frac{dQ_i}{d\phi}$ and $\frac{dU}{d\phi} = \Sigma\frac{dU_i}{d\phi}$ are not being zero at the same time, $\Delta\psi$ over the "singular point" must be $\pi/2$. While, there is little chance for both $\frac{dU}{d\phi}$ and $\frac{dQ}{d\phi}$ to be zero.

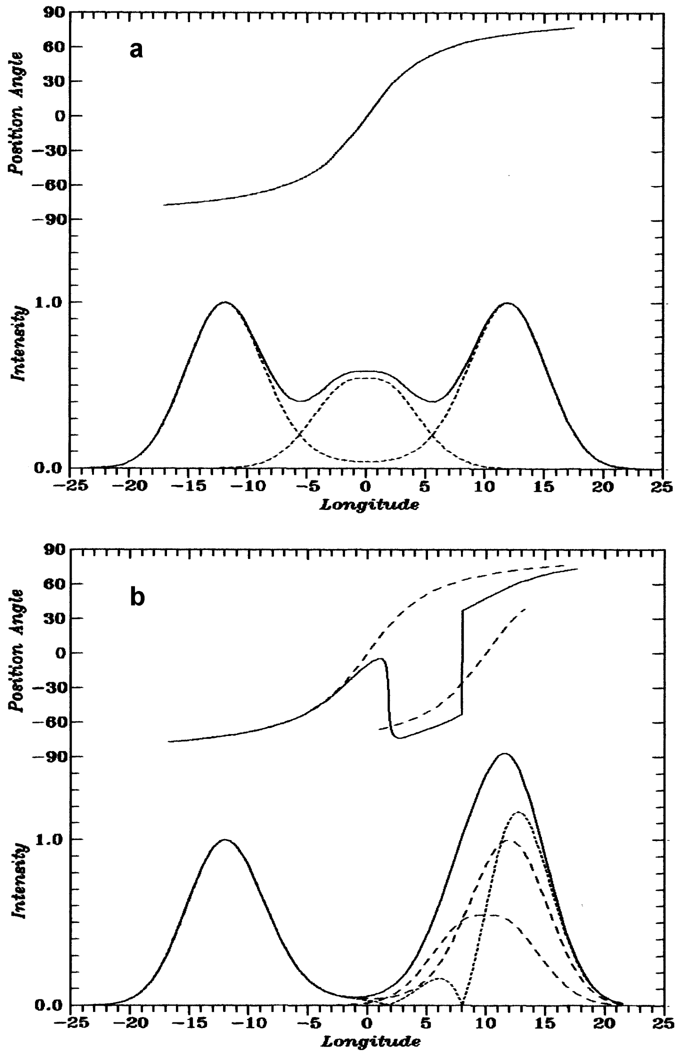

Fig. 3a and b. The simulated profiles and position-angle curves for the cases of: **a** a negligible phase shift; **b** a 10^0 phase shift due to retardation between the core and conal emission-beam components. In the profiles **a**, the curve for linear polarization is the same as the total profile. Two dashed curves indicate the integrated profiles of the beams. In the profile **b**, a short dashed line indicates the total linear polarization, and the two long dashed lines indicate the linear polariations of each beam component. The dashed position-angle curves are of the core and conal beam components.

In the simulations shown in Fig. 3, the relative phase shift $\delta\phi$ between the two beam centers due to retardation effects is taken as: **a** 0^o; **b** 10^o which is quite possible for a real situation.

In our simulations, the inclination angle between the magnetic and rotation axes α is simply taken as being 90^o, the impact angle $\beta = 4^o$, $\phi_2 = 0$. We see in Fig. 3b that when the core emission is coming later than that of the cone, so that there is a phase shift in longitude, the position angle jumps exactly $\pi/2$ as the line of sight goes across one "singular" point (the point near 8^o longitude) where the total linear polarization drops to zero. Moreover, the position angle jumps only mildly (at a longitude near 2^o) as the line of sight passes close to another singular point.

Comparing Fig. 3a and 3b, one can see that if there is no relative phase shift between the two emission beams and if we do not consider any other possibilities for depolarization, the observed profile should be almost completely linearly polarized. When there is a relative phase shift, the depolarization occurs when the two emission components have comparable contributions. In some cases, when both conditions [in Eq. (6)] are satisfied, the observed profile will be highly depolarized, as the case shown in Fig. 3b.

Another example of this kind of simulation has been reported by Xu et al. (1996).

4. Conclusion and discussion

We have shown that if the different emission heights of the core and conal components are considered, there should be a phase shift between their beam centers. That will cause depolarization and position-angle jump(s) in some longitude range of the integrated profile. If the relative phase shifts of three beam centers are investigated (core, inner cone and outer cone), the same conclusion could be obtained, but the simulations and observed situations will be more complicated as the superposition of three, instead of two, beam components are involved.

As subpulses are thought to be emitted from a small emission region of a given beam component (core or cone), then if one observes the polarization of a subpulse around the so-called "singular points", the seperated polarization modes should be obtained. On the one side, the core beam emission dominates, on the other side, the conal emission dominates. The observed position angle of subpulses should more or less concentrate around the dashed position angle curves of the two beam components in Fig. 3b. Though perhaps this is not the orthogonal modes observed over a much larger longitude range (Stinebring et al. 1984a,b); however, due to the relative shift of beam centers, possible non-orthogonal polarization modes should appear over a remarkable longitude range. At a given longitude the position angle of a subpulse can be one of two perpendicular or nearly perpendicular states. The existence of both modes at the same time or rapid transitions between them will also lead to a reduction in the percentage polarization all the way down to nearly zero, as seen from the simulations above.

If only the first condition in Eq. (6) is approximately satisfied at some longitude, that region of the profile can be largely depolarized, but the PA jumps will not be $\pi/2$ as the linear polarization of the integrated pulse cannot be reduced exactly to zero.

What we have considered in this paper is the longitudinal shift of pulsar beam centers caused by retardational delay, however, it seems quite possible that there are other geometrical factors which also produce latitudinal shifts of the beem centers. The different maximum sweep rates of the position-angle curves of the core and conal components seperated by Rankin (1988) imply different impact angles for these beam components, which further suggest latitude shifts of these beam centers.

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