A Possible Interpretation for the Spectral Behavior of Pulsar Average Profiles

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Abstract We present a novel interpretation for the spectral behavior of the average-pulse width on the assumption that the emission is broad band, which is essentially different from the widely accepted narrow-band scenario of "radius-to-frequency mapping". The implication towards the physical processes in the conal emission region is discussed.

Key words pulsar-mode change-spectrum

1 Introduction

The spectral behavior of the mean pulse width (or component separation) has been studied extensively for radio pulsars. Early observations found that the frequency dependence was a power law function or two power laws with a break at a certain frequency (see references in Thorsett 1991). However, after using more complete data, Thorsett modified the relationship to be a smooth form $\Delta\theta = A\nu^{-\alpha} + \Delta\theta_{\min}$, which was further confirmed by the late observations at very high frequency (Xiouris et al. 1996). Most recently, Mitra & Rankin (2002, hereafter MR) reinvestigate this phenomenon. Apart from confirming the relationship introduced by Thorsett for seven widely studied pulsars, they investigate another three pulsars with 'conal' emission and found that the average pulse widths almost do not show narrowing with frequency. So there are two (and at least two) kinds of spectral behavior for the conal emission (Fig.1).

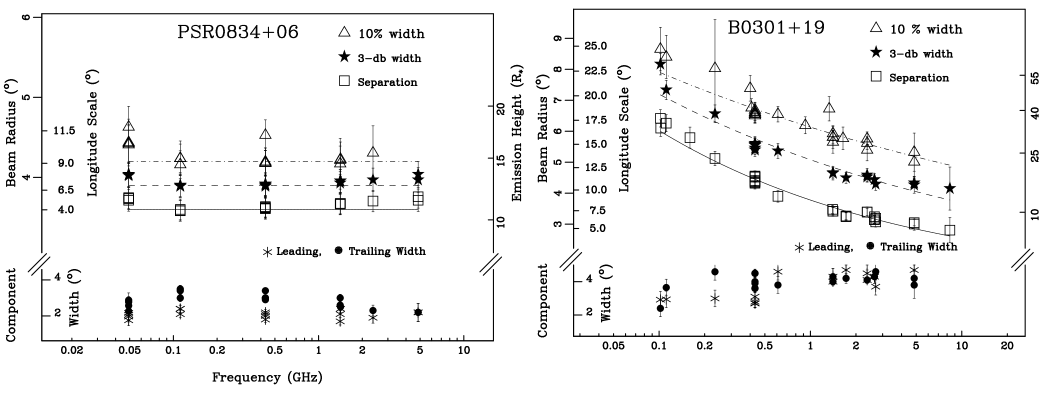

Fig. 1 Observational results for two types of spectral behavior of pulse width (from Mitra & Rankin 2002)

The narrowing of pulse width with frequency is commonly interpreted as a scenario of "radius-to-frequency mapping" (RFM, Cordes 1978), which assumes that the low frequency wave is produced at higher altitudes while the high frequency at lower locations. Many endeavors have been tried to verify the RFM through various observational approaches, e.g., geometry, timing delay and polarimetry (Xilouris et al. 1996 and references therein). Theoretically, a few models predict different forms of RFM. Ruderman & Sutherland (1975) assumed that the radiation frequency is related to the local plasma frequency, thus the emission altitude decreases as $\nu^{-2/3}$ and the component separation varies as $\nu^{-1/3}$. Lyubarskii & Petrova (1998) made the same assumption, but they suggested that refraction due to plasma density gradient could make the frequency dependence of pulse width differ from the $\nu^{-1/3}$ law. In the Inverse Compton Scattering (ICS) model, the RFM and the narrowing of pulse width are predicted for the outer conal component (Qiao & Lin 1998). Generally speaking, regardless of the details of various models, the underlying meaning of any RFM is that, the radiation at a given altitude should be narrow-band compared with the total observed frequency extent, as suggested by Cordes (1978).

The alternative scenario suggests that the radiation is broad band. Rickett & Cordes (1981) proposed that all frequencies may be radiated from the same narrow radial range but the spectrum varies systematically with distance from the magnetic axis. Barnard & Arons (1986) studied models with the broad-band emission from a single radius, which could predict either narrowing (due to refraction) or none-narrowing of pulse width with frequency (due to lack of refraction).

In this paper, we tentatively proposed a new interpretation for the spectral behavior of pulse width under the broad-band assumption. In section 2 we present the details of our interpretation. In section 3 the physical implications are discussed.

2 The Broad-band Interpretation

In a realistic pulsar magnetosphere, the particles created by the pair production process probably follow a wide energy distribution. It was found that particles only undergo significant energy loss near the stellar surface and then move out with energy nearly unchanged (Zhang et al. 1997; Lyubarskii & Petrova 2000). Therefore, the particle energy distribution (PED) hardly changes. These particles produce broad band radiation, leading to a consequence that the observed emission is also broad band at any pulse phase. Even though, it is still possible that at high frequency the emission is too weak to be detected at the outermost phases. This motivates us to take into account such an issue: is the pulse narrowing connected with the variation of the spectral indices at different pulse phases? In fact, at high energy the spectral indices are found to vary with phase (Fierro et al. 1998), but such absolute phase-resolved spectra have not been derived at radio band. The conventional method is to normalize the pulse width at each frequency and then calculate the spectral indices at the relative phase intervals (Lyne & Manchester 1988; Kramer et al. 1994), which do not reflect the property of the emission from the same region. So in the following simulations the phase-resolved spectra are simply assumed. We will demonstrate that the spectral behavior of pulse width could be a by-product of the phase-resolved spectra.

For simplification, let us consider a symmetrical profile composed of two Gaussian components with the same amplitudes and the half power widths. Here the pulsar radio emission is regarded as a simple power law within a frequency extent of $f_{\max}/f_{\min} = 80$, which is similar to the total observing band in MR. Firstly, by assuming a uniform spectral index at all the longitudes, we find that the pulse width and peak separation do not vary with frequency, as shown in Fig.2. This could be easily understood because a uniform power law only reduces the amplitudes by the same ratio so that the centers and the half power widths of the Gaussian components do not change.

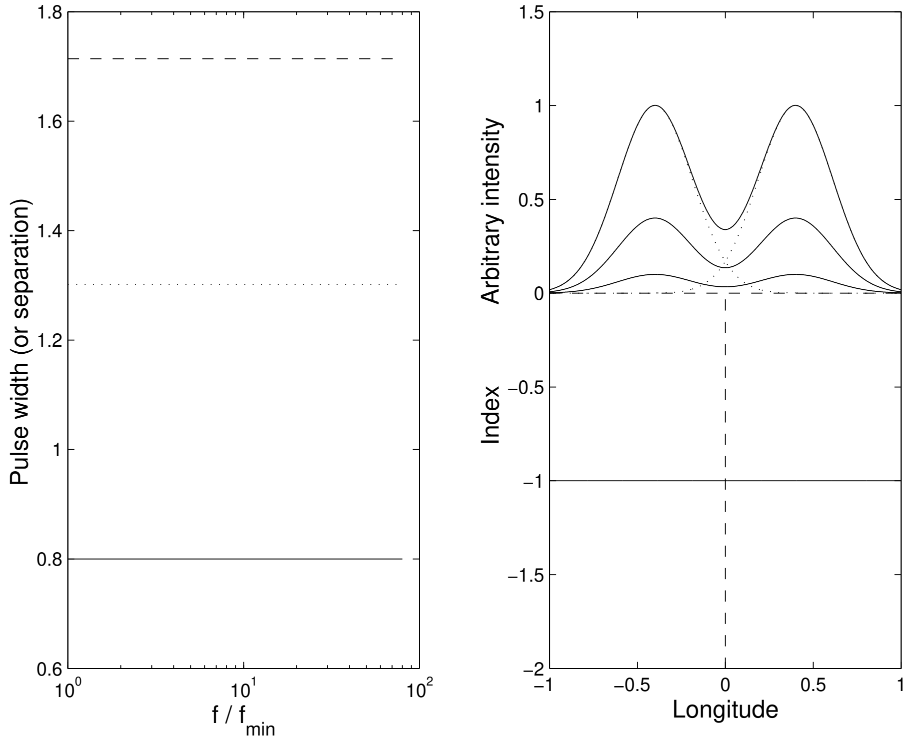

Fig. 2 Right: An uniform power-law index and the evolution of the average profiles shown at three frequencies (without narrowing). Left: the component separation and pulse widths vs. frequency. The dashed, dotted and solid line represent 10% width, 50% width and component separation, respectively.

Then we turn to another case that the spectral index gradually increases from the outer longitudes to the center (longitude=0), as shown in the right panel of Fig.3. Qualitatively, the amplitude at an outer phase reduces faster than that at an inner phase as frequency increases, leading both the peak separation and the pulse width to keep decreasing. The reduction curves of the separation as well as the widths measured at 50% and 10% level of the peak intensities are shown in the left panel of Fig.3.

Comparing our simulations (the left panels of Figs. 2 and 3) with the observation results shown in Fig.1a and Fig.1b respectively, we see that both types of spectral behavior of profile width (or separation) can be reproduced, as long as different forms of phase-resolved spectra are assumed. However, one may question if there is any physical implication of our empirical assumptions. We discuss it in the following section.

3 Physical Implications

In general, a power-law distribution of particles ($N(\gamma) \propto \gamma^{-\mathrm{q}}$) results in a power-law emission intensity ($I(\nu) \propto \nu^{-\mathrm{n}}$). The relationship between the two indices follows $n = (q-1)/2$ no matter via synchrotron radiation, curvature radiation or inverse Compton scattering in the case of incoherent emission (coherent emission will steepen the photon spectrum). Therefore, it is reasonable to think that the phase-resolved spectra actually reflect the PEDs at specific locations in pulsar magnetosphere.

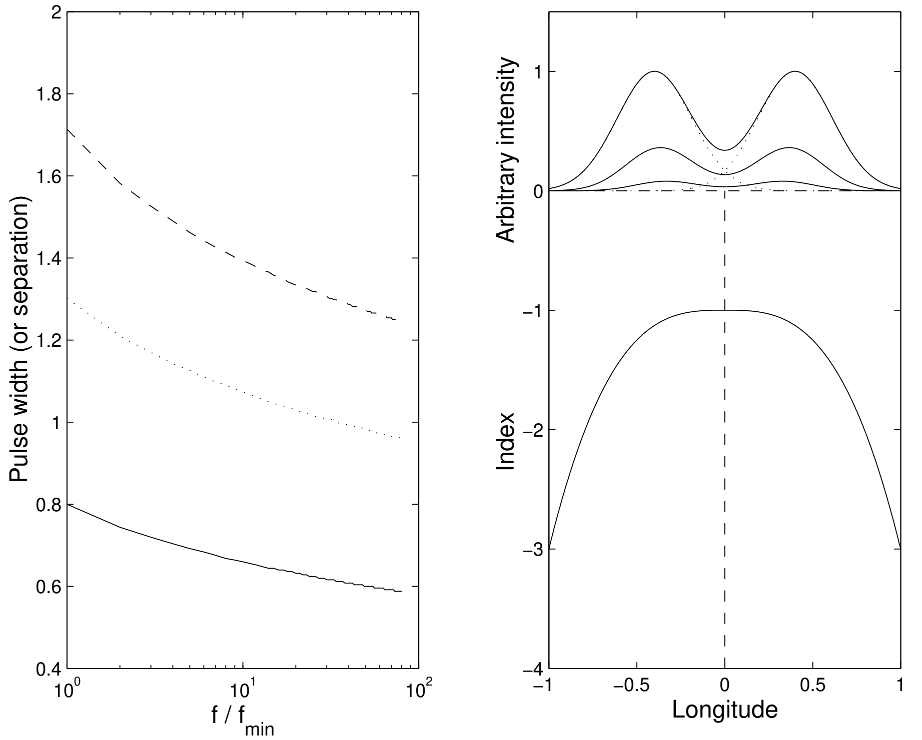

Fig. 3 Right: the variation of power-law index with pulse longitude and the evolution of pulse profiles (the narrowing is clear). Left: cf. Fig.2.

The narrowing of profile needs the PEDs to be nonuniform. Generally there are two kinds of possibility, (1) the PEDs are flatter at lower emission heights, or (2) the PED flattens when the azimuthal angle of the magnetic field (defined as the acute angle between two planes: one containing the magnetic axis and the field line, the other containing the magnetic and rotational axes) decreases. However, the first possibility could be ruled out because of the reasons described at the first paragraph in section 2. The second one is possibly related to the sparking process in the gap from which the secondary particles are produced. It was suggested the energy spectrum of these particles could be remarkably affected by the configuration of the local magnetic fields (e.g., Daugherty & Harding 1983). The detailed process needs to be studied further.

As to the other type of pulsars which exhibit constant pulse width at different frequencies, it requires an uniform PED at different magnetic fields. MR suggested that the pulses of these pulsars are inner conal emission. Then it is puzzling why the outer and the inner conal emission could behave so differently.

To summarize, we present that the frequency dependence behavior of pulse width may be a probe for the PEDs in the conal emission region, which is an interesting problem that has not been extensively studied. Simultaneous observations at multi-frequency bands are expected to test our empirical interpretation. Finally, we suggest that the spectral difference between the leading and trailing conal components observed in some pulsars (Wang et al. 2000 and references therein) may be also related to this issue.

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References

Barnard J.J., Arons J., ApJ, 1986, 302,138
Cordes J.M., ApJ, 1978, 222, 1006
Daugherty J.K., Harding A.K., ApJ, 1983, 273, 761
Fierro J.M., Michelson P.F., Nolan P.L.et al., ApJ, 1998, 494, 734
Kramer M., Wielebinski R., Jessner A.,et al., A&AS, 1994, 107, 515
Lyne A.G., Manchester R.N., MNRAS, 1988, 234,477
Lyubarskii Y.E., Petrova S.A., A&A, 1998, 333, 181
Lyubarskii Y.E., Petrova S.A., A&A, 2000, 355, 406
Mitra D., Rankin J.M., Astro-ph/0205356, 2002
Qiao G.J., Lin W.P., A&A, 1998, 333, 172
Rickett B.J., Cordes J.M., inSieber W., Wielebinski R., eds, Pulsars, 13 years of Research on Neutron Stars. D. Reidel: Dordrecht, 1981, pp.133-140
Ruderman M.A., Sutherland P.G., ApJ, 1975, 196 5
Thorsett S.E., ApJ, 1991, 377, 263
Wang H.G., Han J.L., Qiao G.J., Chinese Astro. & Astrophy. (Pergamon), 2001, 25, 73
Xilouris K.M., Kramer M., Jessner A., et al., A&A, 1996, 309, 481
Zhang B., Qiao G.J., Han J.L., ApJ, 1997, 491, 891