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Pulsar Profiles and Structure of the Emission Region

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Abstract. Recent radio observations of pulsar profiles and the present knowledge about structure of the emission region based on this profiles data are reviewed.

Observations and component structure analysis revealed that there are pulsars profiles having more than 5 components. It call into question that the commonly adopted model of emission region as the double hollow cones and a central core is applicable. Mosaic model of an emission region fit observed profiles with complex more than 5 component structure.

The height (radius) for the emission region evaluated from a dependence of a width of integrated profiles from the pulsar period is estimated as $r_{em} \cong 1.5 \times 10^7 P^{0.1}$ cm.

A comparative analysis of the frequency dependence of the profile widths of millisecond and normal pulsars in 0.1 to 1.4 GHz frequency range indicates that the frequency dependence of a width of their profiles. is much weaker than what is typically observed for normal pulsars. This suggests that the geometry of the emission region of millisecond pulsars is unlike that of normal ones.

1. Introduction

The integrated profiles of pulsars and their frequency and period dependencies characterize a structure and a height of an emission region and may be used for derivation of these data. Recent observations of pulsar profiles and their component structure analysis revealed a new insight to a structure of the emission region.

2. Complex structure of integrated profiles and a model of an emission region

The basic model of pulsar emission region is the hollow-cone model (Radchakrishnan & Cooke 1969, Ruderman & Sutherland 1975). However this model can explain only one- and two-component profiles. Backer (1976) added a center beam. This core-cone model can explain three component profiles. To interpret more complicated profiles Oster & Sieber (1977) postulated the existence of the second concentric cone. Such two-cone-core model can explain up to five component profiles, which was suggested as 'the highest degree of profile complexity (Rankin 1993).

Recent observations and component structure analysis revealed that pulsar profiles have more complex multicomponent structure. The most important points is that there are pulsars profiles having more than 5 components (Kramer et al. 1994; Kuzmin & Izvekova, 1996a,b; Navaro et al. 1997; Kuzmin & Losovsky 1999; Gangadhara et al. 1999, Seiradakis et al. 1999).

Moreover, one may expect that more than 5 component profile structure will be inherent for many pulsars. It is found out, that the number of revealed components depends on the value of signal-to-noise (S/N) ratio (Kuzmin & Losovsky 1999a). Pulsars, which were observed with large S/N revealed more components, that those which were observed with small S/N. It points out to a selection effect. At low S/N the weak components "submerge" into noise and the information on the profile structure is lost. It suggests, that the future most sensitive observations may reveal more pulsars with multicomponent profiles.

More than 5 component structure is of fundamental importance. As regards to observations this is to overcome a generally adopted opinion that "the 5 component profiles represent the highest degree of profile complexity, that the pulsar emission process is apparently capable of producing" (Rankin 1993). As regards to interpretation it call into question the adequacy of the commonly adopted model of emission region as the double hollow cones and a central core, which can not explain more than 5 component structure.

Formally one may suggest 3 or more cone emission zones. But even "two conal emission zones is surprising theoretically and challenges to reexamine this model" (Rankin 1993).

One needs to reconsider the cone-core model and propose a new approach. Such approach was initiated by Manchester (1995). He suggested the emission region as patchy sources with a random distribution of component locations.

Kuzmin & Izvekova (1996a,b) developed this approach and proposed a mosaic structure of an emission region, in which the emission region inside the open cone of magnetic field line represent a mosaic bunch of *permanently located* discrete outflows along the magnetic field lines, injected by *fixed* mosaic patches of localized sparks in the polar cap. The cone of open field lines defines only the boundary of the region in which the emission can exist and thus the total width of the integrated profiles. The intersection of these bunches of emission regions by the observer's line of sight has shaped the observed component structure of the integrated profile. A schematic representation of a mosaic model for the pulsar emission region is shown in Fig.1.

Contrary to the core-two cones model, the mosaic model is physically grounded. According to Ruderman & Sutherland (1975) belief the polar cap discharges form *a group of localized sparks (discrete spots)*, spaced at the distance nearly equals to the height of the polar cap. The size of this spots and the distance between them are approximately equals to the height of a gap. If the gap height is less than the size of the polar cap, a mosaic-like pattern of localized discharges will be formed. The fixed position of the sparks, which one needs to achieve a stable structure of an integrated profile, may be conditioned by pinning the sparks to irregularities of the polar cap or/and magnetic field.

A number of components can be estimated as

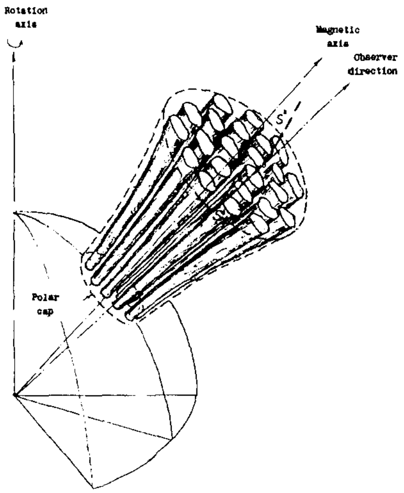

Figure 1. Schematic representation of a mosaic model for the pulsar emission region. The thick dashed curve SS' shows the intersection of the emitting region and the line on sight to the observer.

$$N \cong 2R_p/h \tag{1}$$

where $R_p = R(2\pi R/cP)^{1/2}$ is the radius of the polar cap, R is the radius of a neutron star, h is the height of the polar cap gap. If one adopts after Ruderman & Sutherland (1975) $h = 5\ 10^3$ cm and $R = 10^6$ cm one will obtain $N \cong 6$ for pulsars with period $P = 1$ s, which is in agreement with observations data.

3. A width of integrated profiles and a height of an emission region

Proposed height(radius) for the emission region r_{em} evaluated from theoretical predictions and experimental work range from $r_{em} \approx r_{NS}$- (Sturrock 1970) to $r_{em} \approx r_{LC}$ (Cordes et al. 1983; Kuzmin O. 1989; Smirnova et al. 1996). The width of integrated profiles and its dependence on the period may be used for the independent estimation of r_{em}.

From the equation of magnetic field lines

$$\sin^2 \varphi/r = const, \tag{2}$$

where r and φ are the polar coordinates of a field line, one can obtain the radius of an emission region

$$r = R_{LC}(\sin^2 \varphi/ \sin^2 \varphi_{LC}). \tag{3}$$

Here $r_{LC} = cP/2\pi$ is a radius of the light cylinder, $\sin^2\varphi_{LC} \cong 1$. The opening angle of a cone of open field lines is determined by the tangent to the last open field line

$$\theta = \varphi + \arctan(\sin^2\varphi/\sin 2\varphi). \tag{4}$$

For small φ

$$\theta \cong 3/2\ \varphi, \tag{5}$$

$$\sin\varphi \cong \varphi. \tag{6}$$

Then

$$r \cong cP\varphi^2/2\pi \cong 2cP\theta^2/9\pi. \tag{7}$$

If the emission beam of radio pulsars is confined to the open field line region, the observed profile width W is determined by the opening cone angle θ and α and ζ - angles, formed by the magnetic to the rotation axis and to the direction on the observer, accordingly

$$\cos(W/2) = (\cos\theta - \cos\alpha\cos\zeta)/\sin\alpha\sin\zeta. \tag{8}$$

At $\alpha = \zeta = \pi/2$ the profile width is minimal $W_{min} = 2\theta$. Thus one can obtain an opening angle θ of a radiation cone from the measured value of W_{min}, that is by minimal profile width in $W(P)$ dependence as $\theta = \theta(P) \cong 1/2W_{min}(P)$.

Distribution of $W(P)$ has a relatively well-defined low boundary and large scatter above it. Follow we interpret low bound of $W_{min}(P)$ distribution as the beam opening angle and a scatter as the effect of an inclination of the magnetic to rotation axis. At 102 MHz $W_{min}(P) \cong 10^o P^{-0.45}$ (Kuzmin &Losovsky 1999). Than $\theta(P) \cong 5^o P^{-0.45}$ and the height of an emission region is

$$r_{em} \cong 2cP\theta^2/9\pi \cong 1.5 \times 10^7 P^{0.1} cm. \tag{9}$$

For pulsars with period $P = 1$ s it corresponds to $r_{em} \cong 1.5\times10_{-7} \cong \times10^{-3} r_{LC}$.

This is not far from the estimation of r_{em} based on retardation and aberration (Cordes et al. 1978; Kardashev et al. 1982), but largely apart from those derived from interstellar scintillation (Cordes et al.1983; Kuzmin O. 1989; Smirnova et al. 1996). The cause of this contrast needs for further study.

For millisecond pulsar the approximation of a small φ is inapplicable and the estimation should be made without this simplification. For the shortest period pulsar PSR J0034-0507 ($P = 1.87$ ms) the height of an emission region is $r_{em} \cong 5 \times 10^6$ cm $\cong 0.6 r_{LC}$.

4. Frequency evolution of the integrated profiles and a difference between millisecond and "normal" pulsars

Millisecond pulsars are believed to be a special population of pulsars, which distinguish from normal pulsars by period, their first derivative, magnetic field strength, age and evolutionary history. One may expect that the radio emission

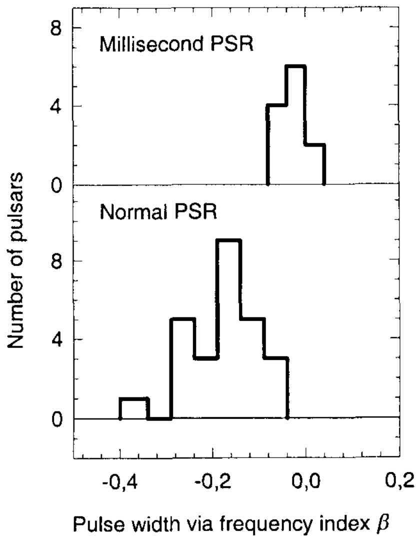

Figure 2. Distribution of the β indexes of the frequency dependence of the profile width of millisecond and normal pulsars.

characteristics of millisecond pulsars will be different from those of normal pulsars as well. However, it is only recently that comparative studies of the radio emission characteristics between millisecond and normal pulsars have appeared in the literature.

Foster et al. (1991); Kuzmin & Losovsky (1996b); Kramer et al. (1998) and Xilouris et al. (1998) indicate that the profile development of millisecond pulsars is rather slow.

Kuzmin & Losovsky (1999a) extends our knowledge of millisecond pulsar profiles to the lowest frequency 102 MHz where such observations have been performed so far. A comparative analysis of the profile frequency dependence indicates that the frequency dependence of a profile width of millisecond pulsars is much weaker than what is typically observed for normal pulsars (Kuzmin & Losovsky 1999b, 2000). They concluded that the weak frequency dependence of the profile width detected in millisecond pulsars is a typical feature of their radio emission.

The comparison of the width-to-frequency dependence $W_{10}(f) \propto f^{\beta}$ indices β between millisecond and normal pulsars is presented in Fig.2.
The mean value of β is $\bar{\beta} = -0.02$ for millisecond pulsars and $\bar{\beta} = -0.17$ for normal pulsars.

The weak frequency dependence of the profile width detected in millisecond pulsars suggests that the geometry of the emission region of millisecond pulsars is unlike that of normal ones.

This indicates that millisecond pulsar emission regions do not simply represent scaled versions of the emission regions of normal pulsars, as already pointed out by other authors.

Kuzmin & Losovsky (1999a, 2000) suggested that the magnetic field configuration in the emission regions of millisecond pulsars is distorted from a dipolar configuration. Kramer et al. (1998) and Xilouris et al. (1998) proposed that the rather slow development of the profiles with frequency suggests very compact magnetospheres.

References

Backer D.C. 1976, ApJ, 209, 895

Cordes J.M. 1978, ApJ, 222, 1006

Cordes J.M., Weisberg J.M. & Boriakoff V. 1983, ApJ, 268, 370

Foster R.S., Fairhead L. & Backer D.C., 1991, ApJ, 378, 687

Gangadhara R.T., Gupta Y.& Lorimer D., 2000, in Proc. IAU Coll. 177, PASP, eds. M. Kramer, N. Wex, R. Wielebinski

Kardashev N.S., Nikolaev N.Ya, Novikov A.Yu., et al. 1982, A&A, 109, 340

Kramer M., Wielebinski R., Jessner A. & Seiradakis J.H. 1994, A&AS, 107, 515

Kramer M., Xilouris K.M., Lorimer D.R., et al. 1998, ApJ, 501, 270

Kuzmin A.D. & Dagkesamanskaja I.M. 1983, Soviet Ast.Letters, 9, 80

Kuzmin A.D. & Izvekova V.A., 1996a, in Proc. IAU Coll.160, PASP, eds. Johnston S., Walker M.A. & Bailes M., 105, 217

Kuzmin A.D. & Izvekova V.A. 1996b, Astronomy Letters, 22, 439

Kuzmin A.D. & Losovsky B. Ya. 1996a, in Proc. IAU Coll.160, PASP eds. Johnston S., Walker M.A. & Bailes M., 105, 285

Kuzmin A.D. & Losovsky B. Ya. 1996b, A&A, 308, 91

Kuzmin A.D. & Losovsky B.Ya. 1999a, Astronomy Reports, 43, 288

Kuzmin A.D. & Losovsky B.Ya. 1999b, Astronomy Letters, 25, 375

Kuzmin A.D. & Losovsky B.Ya. 1999, A&A, 352, 489

Kuzmin O.A. 1989, Ph.D.Thesis, Moscow, Institute for Space Research

Lyne A.G. & Manchester R.N. 1988, MNRAS, 234, 437

Navaro J., Manchester R., Sandhu J.S., et al. 1997, ApJ, 486, 1019

Oster L. & Sieber W. 1977, A&A, 58, 303

Rankin J.M. 1993, ApJ, 405, 285

Radhakrishnan V. & Cooke D.J. 1969, Astrophys.Lett., 3, L225

Ruderman M.A. & Sutherland P.G. 1975, ApJ, 196, 51

Seiradakis J.H., Karastergiou A. & Kramer M. 1999, 2000, in Proc. IAU Coll. 177, PASP, eds. M. Kramer, N. Wex, R. Wielebinski

Smirnova T.V., Shishov V.I. & Malofeev V.M. 1996, ApJ, 462, 289

Sturrock P.A. 1970, ApJ, 164, 529

Xilouris K.M., Kramer M., Jessner A., et al. 1998, ApJ, 501, 286