Chin. J. Astron. Astrophys. Vol. 6 (2006), **Suppl. 2**, 85–89
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

The Shadow of a Pulsar and the Inward Radio Emission in Pulsar Magnetosphere

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Abstract We discuss observational facts that can be interpreted in terms of inward emission in pulsar magnetosphere. These include the main-pulse/interpulse anticorrelation in B1822$-$09 and the locations of emission and absorption features in the pulse profile of B0950+08. Weaknesses of geometrical models employing the inward emission are carefully discussed.

Key words: pulsars: general — pulsars: individual (B0950+08, B1822–09, B1929+10, J0437–4715)

1 INTRODUCTION

The idea of inward radio emission has recently received relatively large interest: Wright (2003) considers it a reasonable possibility in his model of drifting subpulses. He reports that Michel (1992) regarded a core component as a reflection of inward radiation from the star surface. Zhang & Loeb (2004) consider inward radio emission induced by an external object. Levinson et al. (2005) have recently proposed an oscillating model of magnetospheric activity, which implies the same outward and inward radio emissivity.

2 PSR B1822–09

An observational effect that at first sight seems to be a spectacular manifestation of the inward radio emission is provided by PSR B1822$-$09. A strong precursor in the pulse profile of this pulsar is detectable only when a strong interpulse is not, and vice versa (Fowler & Wright 1982; Gil et al. 1994, see figure 4 therein). This makes the impression that both the precursor and the interpulse are emitted from a single source, which intermittently reverses its emission direction – a possibility already considered by Fowler & Wright (1982) and recently discussed in Dyks, Zhang & Gil (2005c). For non-equatorial viewing such a reversal would produce nulling. Periodic reversals could result in subpulse drifting.

So far, the simple geometric idea of inward radio emission has not provided any obvious ways to break through the rich phenomenology of B1822$-$09. It has, however, led us to considering the conditions required to detect obscuration of inward emission by the central plasma cloud containing the neutron star.

3 SHADOW OF A PULSAR?

We limit our discussion of probable absorption features to "double notches" – narrow, W-shaped dips in weak, extended intervals of emission detectable in pulse profiles of B1929+10, J0437$-$4715, and B0950+08 (McLaughlin & Rankin 2004). Wright (2004) has recently showed that a *single* corotating absorber located near the light cylinder can obscure radially extended emission region at two locations, and that these two events can be perceived at two nearby phases. However, the model is disfavoured by the ad hoc location of the high-altitude absorber and by the arbitrary geometry of the emission regions.

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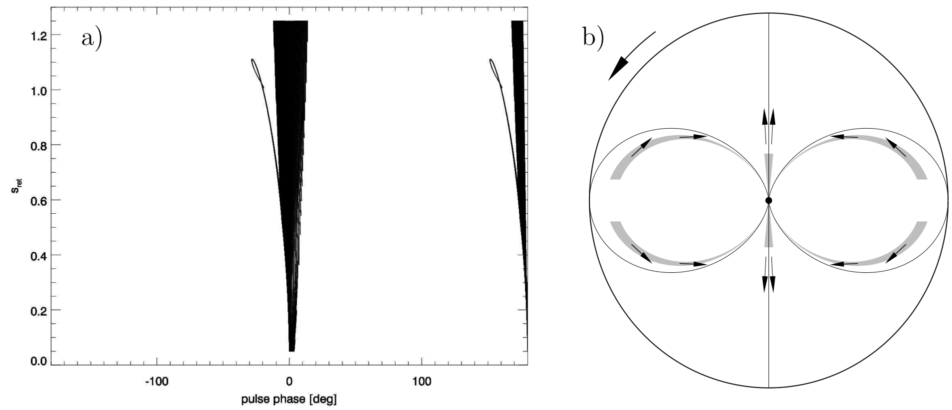

Fig. 1 **a)** Phases at which the plasma-surrounded neutron star eclipses regions of magnetospheric emission (horizontal axis) as a function of the footprint parametr s (vertical axis, $s = 0$ corresponds to the dipole axis and $s = 1$ to the last open field lines). Note that for inward emission from magnetic field lines with $s \simeq 1.1$, the possibility of double eclipse (small loop) appears on the leading side of the main radio pulse (expected near $\phi = 0$). **b)** Emission geometry required for the double eclipse event (with inward emission regions extending between $s = 1.05$ and 1.085), as invoked from panel a).

The model we present in Dyks et al. (2005a, hereafter DFSRZ) assumes that: 1) it is the central plasma cloud (containing the neutron star) that eclipses the emission region and produces the notches, and 2) the inward emission is tangent (in the corotating frame) to the corotating, dipolar magnetic field. Equipped with only these two assumptions it is possible to calculate the phases at which shadows of a pulsar can appear in a pulse profile. In DFSRZ we performed such calculation *for the entire volume of the light cylinder* (without specifying any emission region within it).

Our result for the equatorial plane of orthogonal rotator is shown in Figure 1a which presents the phases of eclipse (horizontal axis) as a function of the footprint parameter s of magnetic field lines (vertical axis).

It is surprising that this kind of calculation (based on so few assumptions) already reveals the possibility of double eclipse, which can be recognized as the small loop near $\phi = -25°$. The double eclipse can occur if the inward radio waves are emitted from a flaring funnel occupying a narrow range of footprint parameter near $s \simeq 1.1$ (located near the last open field lines in the closed field line region, see Figure 1b).

For a broad range of large dipole inclinations α between $\sim 70°$ and $\sim 120°$, the double eclipse can occur on the leading side of the main radio pulse, which is where we observe the double notches for B0950+08. The flaring funnel geometry implied by Figure 1a reproduces quite well the general morphology of the radio pulse profile of B0950+08 (Figure 2, calculated for $\alpha = 70°$ and with ζ marked at $120°$). Moreover, the inward emission direction is qualitatively consistent with the *leftward* shift of position angle curve, noticeable for B0950+08 and B1929+10 (the shift has the opposite direction than predicted by Blaskiewicz, Cordes & Wasserman (1991); see section 6 in DFSRZ). A similar effect (opposite to that described by Blaskiewicz et al.) was also identified by Navarro et al. (1997) for J0437−4715, in spite of its erratic position angle curve.

The double notches in J0437−4715 and B1929+10 lag the main radio pulse (MP) by some $100°$. According to our model, the shadow of a pulsar can be observed far on the trailing side of the MP only in the nearly aligned geometry, when $\alpha \sim \zeta \lesssim 20°$ (ζ is the viewing angle). Although very small dipole inclinations have been proposed for both these objects (Gil & Krawczyk 1997; Lyne & Manchester 1988), a good deal of arguments can be found for larger α (close to $\sim 40°$ for J0437−4715, Navarro et al. (1997), and possibly as large as $\sim 90°$ for B1929+10, Rankin & Rathnasree 1997). So large α cannot be accommodated in our model, at least as long as we stick to the dipolar magnetic field, and the possible emission region is limited to the interior of the light cylinder.[1]

[1] Emission from regions outside the light cylinder can also be pulsed – cf. Kirk et al. (2001).

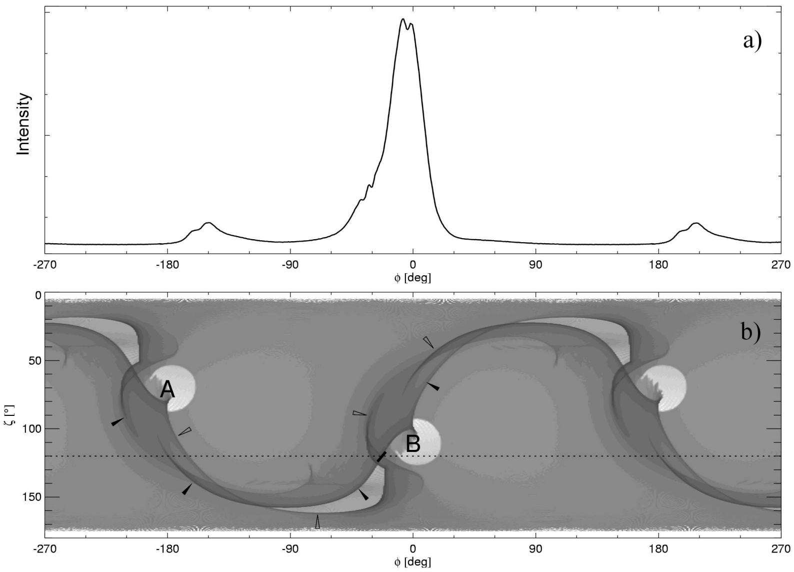

Fig. 2 **a)** Averaged pulse profile of B0950+08 observed at 430 MHz by McLaughlin & Rankin (2004). Note the double notch feature on the leading wing of the main radio pulse. **b)** (ϕ, ζ)-distribution of inward emission from magnetic field lines with $s = 1.15$ (result for $\alpha = 70^\circ$). The short dash left of pole B marks the location of double eclipse. The observed profile can be roughly reproduced if the observer is located at $\zeta \simeq 120^\circ$ (dotted horizontal).

To observe the eclipse far on the trailing side of the MP, the eclipsed radiation must be emitted from large radial distances $r \sim 3R_{\rm lc}$ from the neutron star. The associated propagation time then results in the large phase delay. It has not been determined whether a *double* eclipse is possible in this case, mainly because the geometry of the emission region in the complex magnetic field at large distances is ambiguous.

An extreme variant of the "pulsar shadow" idea is the possibility that the famous hollow cone shape of radio beams is observed because their central parts are obscured by the plasma cloud + neutron star system. For the radius of the opaque region $r_{\rm opq} \lesssim 10R_{\rm NS}$, the observed radio pulse profile would actually be a gravitationally-lensed image of the radio emission region.

4 HIGH-ENERGY DIGRESSION

It is perhaps worth to mention that similar pulse profiles (with the low-level extended emission and the interpulses separated by significantly less than 180°) have been observed for long time in the high-energy bands for the Crab and Vela, and it is these gamma-ray pulsars for which some unorthodox ideas were tried out first.[2] The inward emission has often been present in those efforts. For example, the two-directional emitter (proposed for the MP-IP anticorrelation in B1822$-$09) was already considered by Cheng & Ruderman (1977) to explain the asymmetry of the high-energy profile of the Crab pulsar. Then it became a basic (but sometimes unwelcome – see section 1 in Dyks et al. 2005b) ingredient of the outer gap model (figrue 7 and next in Cheng, Ho & Ruderman 1986). The bulk of observed X-ray luminosity has been interpreted in terms of synchrotron emission from electron-positron pairs created on *closed* field lines all around the neutron star (Wang et al. 1998; Cheng, Gil & Zhang 1998). A bold idea of "inward hollow cone" can be seen in figure 5 of Chen, Ruderman & Zhu (1998). Recently, the inward emission from the radially extended outer gaps has been used to interpret selected components of the X-ray profile of the Vela pulsar (Dyks et al. 2005b; Romani et al. 2005).

[2] Probably because the two then-known high-energy pulse profiles were so different from the usually narrow radio pulse profiles.

5 A HANDFUL OF SELF-CRITICISMS

Our model (DFSRZ) has been created as a more natural alternative to the model of Wright (2004). It is nevertheless challenged by the following observational facts:

1. Trailing location of the double notches (observed in two, out of the three notched pulsars). This requires the nearly aligned geometry which seems unnatural at least for B1929+10.
2. The specific W-shape of the notches. To get two solutions for the eclipse is one thing; to show that the W-shape is preferred is another.
3. The high polarization degree and the simple position angle curve. The formation of double notches requires that radiation emitted from different altitudes (and therefore polarized at different angles) is detected at nearby phases in a pulse profile. In the same way the double peaks in gamma-ray profiles of pulsars are believed to originate (eg.: Romani & Yadigaroglu 1995). This cumulation tends to depolarize the observed radiation and to produce fast changes of position angle (Dyks, Harding & Rudak 2004).
4. The large radial extent of coherent radio emission region and the large emission altitude. This is problematic for some coherency models, but not for all of them. For example, by dragging the high-altitude plasma into the electromagnetic radiation emitted at lower altitudes, the rotational effects make conditions favourable for operation of the free electron laser mechanism, which works in $B \lesssim 10^2$ G (Fung & Kuijpers 2004).
5. The location of emission within the closed field line region (see Figure 1b) which is usually considered as a 'dead' zone. According to the outer gap model of the high-energy emission, however, the region is a place of copious production of pairs (see figure 3 in Wang et al. 1998 or figure 2 in Cheng & Zhang 1999).

None of these issues definitely kills the model, though they should be a source of concern.

6 WEAK AND WIDE BEAMS

In spite of the problems listed in Section 5 we decidedly promote here a non-standard origin of the weak emission extended over a large range of phases in PSR B0950+08, B1929+10, and J0437−4715.[3] Given that the objects are among the closest and brightest known pulsars, we may be able to see more in these objects than in other ones (although not every pulsar is equipped with this additional emission, as the nearby Vela pulsar seems to suggest).

Jinlin Han has recently drawn our attention to PSR J2124−3358 which has the most complicated profile among the nine millisecond pulsars observed by Manchester & Han (2004). The profile doubtlessly challenges the traditional classification scheme, and we find, (not surprisingly), that it belongs to the closest and intrinsically the dimmest object in their sample.[4]

Because of some of its general properties (eg. the leftward shift of the PA curve) the inward radiation still presents a possible interpretation of the weak and extended emission. For example, a model with inward radiation from the standard radio emission region, scattered in various directions off the central object may appear promising. A good model of the weak and extended emission would probably provide a lot more stringent geometry indicator than the present-day polar cap model.

Acknowledgements This work was supported by PBZ-KBN-054/P03/2001 (JD, MF and AS), 2P03D. 004.24 (BR), and by NASA under grants NNG05GB67G, NNG05GH92G, and NNG05GH91G (BZ).

[3] By 'non-standard' we mean: different than the widely discussed variants of the polar cap model, eg. the nearly aligned geometry or the complicated "sun-spot-like" distortions of the magnetic field. The latter are disfavoured by the nearly textbook PA curves of B0950+08 and B1929+10: when corrected for effects of the orthogonal polarization modes, the curves closely follow the shape given by the Radhakrishnan & Cooke (1969) model.

[4] The low radio luminosity is expected when the observer misses the bright and narrow standard radio beam. This is *not* the case for B0950+08, B1929+10 and J0437−4715.

References

Blaskiewicz, M., Cordes, J. M., Wasserman I., 1991, ApJ, 370, 643
Chen, K., Ruderman, M., Zhu, T., 1998, ApJ, 493, 397
Cheng, K. S., Gil, J., Zhang, L., 1998, ApJ, 493, L35
Cheng, K. S., Ho, C., Ruderman, M., 1986, ApJ, 300, 500
Cheng, A. F., Ruderman, M., 1977, ApJ, 216, 865
Cheng, K. S., Zhang, L., 1999, ApJ, 515, 337
Dyks, J., Frąckowiak, M., Słowikowska, A., Rudak, B., Zhang, B., 2005a, ApJ, 633, 1101 (DFSRZ)
Dyks, J., Frąckowiak, M., Słowikowska, A., Rudak, B., Zhang, B., 2005b, AIP Conference Proceedings, 801, 265
Dyks, J., Harding, A. K., Rudak, B., 2004, ApJ, 606, 1125
Dyks, J., Zhang, B., Gil, J., 2005c, ApJ, 626, L45
Fowler, L. A., Wright, G. A. E., 1982, A&A, 109, 279
Fung, P. K., Kuijpers, J., 2004, A&A, 422, 817
Gil, J., Jessner, A., Kijak, J. et al., 1994, A&A, 282, 45
Gil, J., Krawczyk, A., 1997, MNRAS, 280, 143
Kirk, J. G., Skjaeraasen, O., Gallant, Y. A., 2002, A&A, 388, L29
Levinson, A., Melrose, D., Judge, A., Luo, Q., 2005, ApJ, 631, 456
Lyne, A. G., Manchester, R. N., 1988, MNRAS, 234, 477
Manchester, R. N., Han, J. L., 2004, ApJ, 609, 354
McLaughlin, M. A., Rankin, J. M., 2004, MNRAS, 351, 808
Michel, F. C., 1992, in Hankins T. H., Rankin J. M., Gil J. A., eds, The Magnetospheric Structure and Emission Mechanisms of Radio Pulsars, Pedagogical Univ. Press, Zielona Góra, p. 236
Navarro, J., Manchester, R. N., Sandhu, J. S. et al., 1997, ApJ, 486, 1019
Radhakrishnan, V., Cooke, D. J., 1969, Astrophys. Lett., 3, 225
Rankin, J. M., Rathnasree, N., 1997, J. Astrophys. Astr., 18, 91
Romani, R. W., Kargaltsev, O., Pavlov, G. G., 2005, ApJ, 627, 383
Romani, R. W., Yadigaroglu, I.-A., 1995, ApJ, 438, 314
Wang, F. Y.-H., Rudeman, M., Halpern, J. P., Zhu, T., 1998, ApJ, 498, 373
Wright, G. A. E., 2003, MNRAS, 344, 1041
Wright, G. A. E., 2004, MNRAS, 351, 813
Zhang, B., Loeb, A., 2004, ApJ, L53