Chin. J. Astron. Astrophys. Vol. 6 (2006), **Suppl. 2**, 90–96
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Possible New Clues towards Understanding Pulsar Radio Emission

Bing Zhang ⋆

Department of Physics, University of Nevada, Las Vegas, USA

Abstract The origin of pulsar radio emission has been a mystery for more than 35 years. The observed extremely high brightness temperatures strongly suggest that the radio emission must be highly coherent, but the real mechanism in operation has been evading identification. Instead of trying to solve this decades long problem, here I discuss several recent new observations and the ideas to interpret them, which shed new light on understanding pulsar radio emission. The topics include (1) a recent XMM-Newton observation of the famous, old-drifting PSR B0943+10 and its physical implications; (2) models to interpret the radio flaring activity of the pulsar B in the double pulsar system PSR J0737–3099; (3) possible identification of the inward radio emission from some pulsars; and (4) the suggestion that GCRT J1745–3009 is a white dwarf pulsar. Two possible interpretations to the recently identified Rotating RAdio Transients (RRATs) are also proposed.

Key words: pulsars: general — pulsars: individual (PSR B0943+10, J0737–3039B, B0950+08, B1822–09) — stars: neutron — white dwarfs

1 INTRODUCTION

Pulsar radio emission is probably the least understood astrophysical phenomenon. While in most other fields in astrophysics theorists are using data to constrain detailed model parameters, radio pulsar theorists are still struggling to identify the right mechanism at work. The enormously high brightness temperatures observed in pulsars require that the emission must be coherent. Since there is no analogue in other astrophysical environment (such as from the Sun), identifying the right pulsar coherent mechanism has been a rather challenging work. More than a dozen of models have been proposed in history, which may be broadly grouped into three main categories, i.e., antenna (or bunching) mechanisms, relativistic plasma emission mechanisms, and maser mechanisms. However, most of these models even have trouble to reproduce the right frequency of coherent emission, let alone to interpret many, very detailed multi-wavelength observations. Radio data are very abundant, but more and more detailed observations are NOT what is needed to help with theoretical modelling. As reviewed by Melrose (1995, 2004), neither the "bottom-up" approach (starting from the first principles) nor the "top-down" approach (starting from the radio data) are likely to be very helpful in identifying the right mechanism in operation. This is probably the astrophysics field with the highest data-to-theory contrast.

Here we make no attempt to solve this decades long problem. Rather, we discuss several recent interesting new observations and the new ideas to interpret them. These seemly independent pieces of information, when putting together, would provide some possible new clues to understand the mystery of pulsar radio emission.

2 XMM-NEWTON OBSERVATION OF PSR B0943+10

Most radio pulsar emission beams are narrow, referring to a low emission altitude (Kijak & Gil 2003). A pair plasma streaming from the polar cap region is likely the agent to power the conventional radio emission (Ruderman & Sutherland 1975, hereafter RS75). However, the type (e.g. whether a pure vacuum gap or a

⋆ E-mail: bzhang@physics.unlv.edu

space charge limited flow) of the inner gap has been difficult to infer based on the radio data alone. Different inner gap models, on the other hand, predict different thermal X-ray luminosities due to polar cap heating (Zhang, Harding & Muslimov 2000). X-ray observations therefore open the window to study pulsar inner gaps in great detail.

PSR B0943+10 is an old pulsar ($P = 1.10\,\mathrm{s}$, $\dot{E} = 1.0 \times 10^{32}\ \mathrm{erg\ s^{-1}}$, $\tau = 5.0\,\mathrm{Myr}$, $B_p = 4.0 \times 10^{12}\,\mathrm{G}$) that clearly displays regular subpulse drifting. Deshpande & Rankin (1999) have closely monitored the drifting pattern and revealed the "polar cap map" of this pulsar. The radio data require 20 sparks rotating counterclockwise with a period of 37 rotation periods. Sparks have long been invoked within the vacuum gap model (RS75; Gil & Sendyk 2000). Such a model predicts a very high thermal X-ray luminosity from the polar cap region if the pulsar is a neutron star. Alternatively, it has been suggested that drifting pulsars might be bare strange stars so that the so-called "binding energy problem" of the vacuum gap model is naturally avoided (Xu, Qiao & Zhang 1999). In such a picture, the thermal heat is quickly spread out to the full strange star surface due to the large electron thermal conductivity, so that no hot spot is expected (Xu, Zhang & Qiao 2001).

Since different models predict rather different X-ray emission properties, a dedicated X-ray observation would differentiate among the models and shed light into the inner gap harboring at the vicinity of the pulsar polar cap region. Zhang, Sanwal & Pavlov (2005, hereafter ZSP05) performed a ~ 33 ks observation to PSR B0943+10 with the *XMM-Newton* observatory. We detected the pulsar, and with 102 counts, we were able to perform spectral fits to the data. Although the spectrum may be also fitted by a non-thermal spectrum, we found that a thermal fit gives a bolometric luminosity $\sim 5 \times 10^{28}\ \mathrm{erg\ s^{-1}}$ and a surface area of $\sim 10^3 (T/3\mathrm{MK})^{-4}\ \mathrm{m}^2$, which is much smaller than the conventional polar cap area. The thermal radiation can be interpreted as emitted from footprints of sparks drifting in an inner gap of a height $h \sim (0.1{-}0.2) r_{\rm pc}$, where $r_{\rm pc}$ is the radius of the conventional polar cap (ZSP05). Figure 1 shows the confidence contours (68%, 90%, and 99%) for the blackbody-fit parameters.

The results have important implications. First, the small emission area indicates that there is indeed an inner gap operating near the surface, which likely powers the conventional radio emission. Second, the X-ray luminosity and the emission area are both consistent with the subpulse drifting data (e.g. $\hat{P}_3/P$) within a particular type of polar cap model (ZSP05; Gil, Melikidze & Geppert 2003; Gil, Melikidze & Zhang 2006a,b, also in these proceedings). This gives encouraging support of the existence of "sparks" or polar

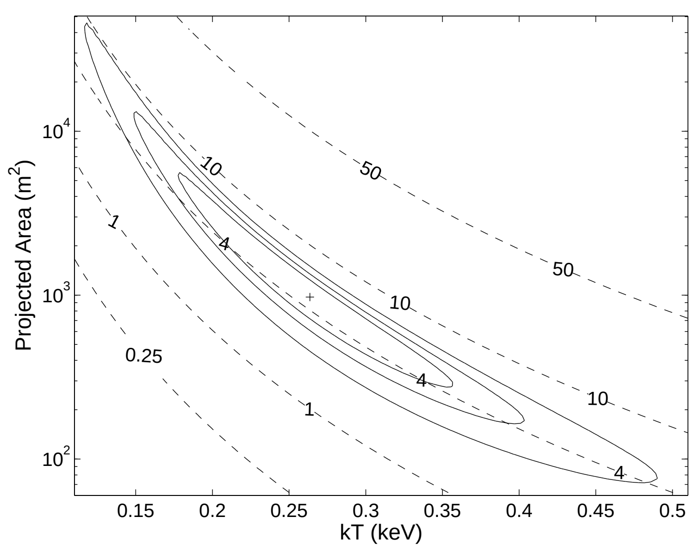

Fig. 1 Confidence contours (68%, 90%, and 99%) of the blackbody-fit parameters for the X-ray emission from PSR B0943+10. From Zhang, Sanwal & Pavlov (2004).

cap "storms" in this pulsar. Finally, comparing with the data, the pure vacuum gap (VG) model predicts too high a luminosity (RS75) and the space charge limited flow (SCLF) model predicts too low a luminosity (Harding & Muslimov 2001, 2002). The data requires that the inner gap has a property intermediate between the VG and SCLF, i.e. the gap is partially screened (Cheng & Ruderman 1980; Usov & Melrose 1996; Gil et al. 2003, 2006a,b; ZSP05). The small area of the hot spot and the requirement to reproduce the correct drifting rate suggest that the near-surface magnetic field configuration is likely more complicated than dipolar and may have stronger multi-pole field components (e.g. Gil & Mitra 2001). Due to the detection of a small hot spot, the bare strange star scenario is disfavored.

One caveat is that the non-thermal origin of the spectrum is not ruled out. Much longer exposure for this pulsar and observations of other similar, old, drifting pulsars are needed to verify the interpretation proposed by ZSP05 and Gil et al. (2006a,b). Nonetheless, it is impressive how the partially-screened inner gap sparking model could perfectly match both the radio and the X-ray observations. An interesting finding from the study of many drifting pulsars (Gil et al. 2006a,b) is that the polar cap heating model for a partially-screened inner gap can also give rise to the familiar empirical X-ray luminosity law $L_{\rm x}/\dot{E} \sim 10^{-3}$ (Becker & Trümper 1997), which has been traditional interpreted as of magnetospheric origins (Cheng, Gil & Zhang 1998; Zhang & Harding 2000).

3 INTERPRETING THE ORBIT-MODULATED FLARING ACTIVITY OF J0737–3039B

The discovery of the double pulsar system PSR J0737–3039A&B (Burgay et al. 2004; Lyne et al. 2004) opens a new window to study relativity and pulsar magnetospheres (A. Lyne, in these proceedings). One particularly interesting phenomenon is that the pulsar B re-brightens at certain orbital phases, suggesting that the radio emission of pulsar B is somewhat related to the interaction between both pulsars. Understanding the origin of such rebrightening is therefore essential to understand the poorly known emission site and mechanism of pulsar radio emission. So far there are four suggestions to interpret this peculiar behavior and we shall comment on them in turn according to the order when they were suggested.

- Jenet & Ransom (2004) suggested that the pulsar B rebrightens when the pulsar A radio beam illuminates it. Physically, it is hard to trigger strong coherent emission by a radio wave. It might be possible that the gamma-ray beam aligns with the radio beam in A, so that the gamma-ray beam of A triggers a pair cascade in B's magnetosphere and therefore makes the rebrightening of B (Jenet & Ransom 2004). Zhang & Loeb (2004) explored such a possibility in greater detail and found that the number of pairs produced by such a process is negligible compared with the number of pairs produced intrinsically in B's magnetosphere. Such a scenario is therefore not favored.
- Lyutikov (2004) suggested that the rebrightening occurs when the line of sight runs parallel to the outer magnetic field lines of B combed by the strong A wind. The mechanism is the Cherenkov-drift instability proposed by Lyutikov et al. (1999). This model is incorrect simply because it predicts a very wide double cone emission that is inconsistent with the very small duty cycle of the B pulse profile (Lyne et al. 2004).
- Zhang & Loeb (2004) suggested that a small fraction of the particles in the A wind leak into B's magnetosphere. These particles then stream down towards the B's surface and emit coherent emission (likely due to a two-stream instability) at an altitude of about $\sim 10^8$ cm. Zhang & Loeb (2004) showed that the pulsar A wind is so powerful that only a very small fraction of the leaked particles could dominate the intrinsic pair production in B's magnetosphere.
- Alternatively, the pulsar B may be intrinsically radio bright all the time, but the emission beam in most occasions misses the line of sight. The pulsar A wind serves to modulate the pulsar B emission beam, and the rebrightening is when the bright beam sweeps the line of sight. This idea was first suggested by Spitkovsky & Arons (2004) and later elaborated by Lyutikov (2005).

The last two models are currently the most attractive suggestions to interpret the data. Identifying the correct model between the two would have profound implications to understand pulsar radio emission. If Zhang-Loeb model is correct, then pulsar radio emission models should allow inwardly-beamed emission propagating through the magnetosphere and reach the observer on the other side of the neutron star. This is consistent with the recent tentative identification of the inward radio emission in isolated pulsars (Dyks et al. 2005a, b, see Section 4 for more discussion). If the model involving an intrinsically radio-bright pulsar is correct, the radio emission region should be confined at a low emission altitude and the coherent mechanism should be immune from the strong interaction between A wind and B's outer magnetosphere. This would rule out the radio emission models that only work at outer magnetosphere (e.g. Lyutikov et al. 1999). Given an energetically dominant pulsar A wind, it seems unlikely (at least to the author) that the wind only modifies the field line configuration without influencing or even destroying the fragile coherent emission from B.

4 INWARD RADIO EMISSION IN ISOLATED PULSARS

In the traditional pulsar emission models, particles are believed to stream from the polar cap region all the way to the light cylinder in the open magnetic field lines. The broad band emissions (gamma-rays, X-rays, optical, and radio) observed from pulsars are, by default, believed to be beamed "outwards", i.e. away from the pulsar. The Zhang-Loeb model invokes an externally-triggered "inward" emission, i.e., the emission beaming towards the pulsar and reaching the observers on the other side of the pulsar. The idea is speculative in its own. However, some recent modelling of two peculiar phenomena led to the tentative identification of the inward radio emission even in isolated pulsars (Dyks et al. 2005a, b, see also J. Dyks, in these proceedings). This also lends indirect support to the model suggested by Zhang & Loeb (2004).

The evidence for pulsar inward emission comes from the interpretations of two independent pieces of data, which have been rather mysterious within the framework of pulsar outward emission. The first mystery was the so-called "double-notch" phenomenon identified in several nearby pulsars, e.g. B0950+08, B1929+10, J0437–4715 (Navarro & Manchester 1996; Rankin & Rathnasree 1997; Navarro et al. 1997; McLaughlin & Rankin 2004). The double notches have the appearance of absorption dips, or eclipse dips: they look like slots carved in a continuous emission pattern (Figure 2a). The phase at which the double notches occur, their depth, as well as the width all weakly depend on the observation frequency. Such kind of features are consistent with the picture that the radio emission pattern is absorbed by an intervening absorber between the emitter and the observer in the pulsar vicinity. Within the traditional outward emission picture, one has to introduce an ad hoc absorber sitting in the pulsar magnetosphere (Wright 2004). Nobody knows what the absorber would be and why it should be there. The picture changes dramatically if one accepts the idea that some of the observed radio emission pattern is produced by inward emission. In such a picture, *the pulsar itself is the absorber.* In order to test the idea, Dyks et al. (2005a) numerically calculated the observational pulse profile as well as the location of the double notch by assuming inward emission from the pulsar magnetosphere. Without any ad hoc assumptions, the predicted location of the pulsar shadow is at $20°$–$30°$ before the main radio peak, exactly where the double notch is observed in PSR B0950+08. This is the first direct evidence that the broad enigmatic emission component in the pulse profile of PSR B0950+08 is beamed inwardly.

Another independent piece of evidence for pulsar inward emission is from the peculiar mode-changing phenomenon observed in PSR B1822–09 (Gil et al. 1994). The pulse profile of this pulsar includes three components, a "precursor" at the phase $17°$, a main pulse at the phase $33°$, and an inter-pulse at the phase $215°$. The peculiarity of the pulsar is the strong anti-correlation between the intensities of the precursor and the inter-pulse, i.e. when the precursor enters the nulling state, the inter-pulse becomes visible, and vice-versa (Figure 2b). This phenomenon has puzzled pulsar researchers for over 10 years. Although suggestions invoking both near-orthogonal rotators and near-aligned rotators have been suggested, none of the models could interpret the phenomenon self-consistently (see Dyks et al. 2005b for a review). Recently, Dyks et al. (2005b) proposed an elegant interpretation to the peculiar phenomenon, which invokes the reversal of the radiation direction for the precursor-inter-pulse component, which naturally solved all the previous problems in the near-orthogonal and the near-aligned models. According to this picture, one of the component in the precursor/inter-pulse must beam towards the direction of the pulsar itself. In other words, one expects inward emission.

With the realization of the inward emission, the basic picture of pulsar radio emission needs modification. It is possible that the main emission components (e.g. core and conal components) are still the traditional outward emission. Nonetheless, the inward emission may contribute to the broad emission features detected in nearby pulsars (such as B0950+08). Some emission components may reverse their directions

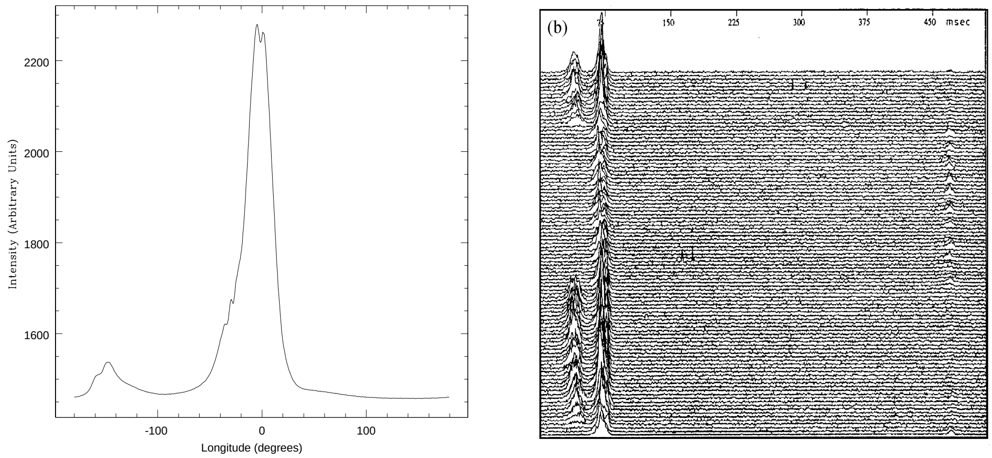

Fig. 2 Observational evidence of pulsar inward emission. (a) The double notches observed in PSR B0950+08. The notches are near the phase -30°. From McLaughlin & Rankin (2004). (b) The peculiar mode changing in PSR B1822$-$09. From Gil et al. (1994).

(such as B1822–09). The well-known "nulling" phenomenon observed in many pulsars may be simply a result of emission direction reversal (Dyks et al. 2005a, b).

Physically, inward emission implies an inwardly-directed particle flow. The magnetospheric current flow may be intrinsically oscillative (Levinson et al. 2005). The annular polar cap flow from the field lines that cross the null charge surface may be the agent to generate such oscillative currents (e.g. Qiao et al. 2004).

5 GCRT J1745–3009 AS A TRANSIENT WHITE DWARF PULSAR

A completely different phenomenon would also shed light on pulsar radio emission. Recently, Hyman et al. (2005) discovered a mysterious transient radio source, i.e. GCRT J1745–3009, in the direction of the Glactic center. This source exhibited five peculiar consecutive outbursts at 0.33 GHz with a period of 77.13 minutes and a duration of ~ 10 minutes for each outburst. The radiation is very likely coherent as long as the distance is larger than 70 pc. Although many efforts have been made to interpret it (Hyman et al. 2005; Zhu & Xu 2005; Turolla et al. 2005), this behavior is hard to understand in a straightforward way within the framework of known astrophysical objects. Hyman et al. (2005) therefore claims that this source is the prototype of a hitherto unknown class of transient radio sources.

Zhang & Gil (2005) suggested that GCRT J1745–3009 is very likely a white dwarf pulsar (WDPSR). These are white dwarfs with very strong dipolar magnetic fields that can form a "lighthouse" beam just like neutron star pulsars. Within this model, the apparent 77.13-minute period is simply the rotation period of the white dwarf, and the 10-minute flaring duration corresponds to the epoch when the radio beam sweeps our line of sight. Assuming a surface dipolar field of $\sim 10^9$ G, we show that the spin-down parameters GCRT J1745–3009 place it slightly below the pair production deadline for white dwarfs. The bursting epoch corresponds to the episodes when stronger sunspot-like magnetic fields emerge into the white dwarf polar cap region during which the pair production condition is satisfied and the white dwarf behaves like a radio pulsar. It switches off as the pair production condition breaks down.

If the Zhang-Gil model is correct, it suggests that high-brightness coherent radio emission is not unique for neutron star pulsars. A coherent mechanism similar to that operating in neutron star pulsars should also apply in a very different environment, i.e. in white dwarfs. Table 1 summarizes a comparison between the properties of neutron star pulsars and those of putative white dwarf pulsars.

Table 1 Comparison between the Typical Neutron Star Pulsars (NSPSRs) and the Putative White Dwarf Pulsars (WDPSRs)

Parameter	NSPSRs	WDPSRs
Brightness temperature (T_B)	$\sim 10^{25}$ K	$\sim 10^{15}$ K
Period (P)	~ 1 s	~ 1 h
Surface field (B_p)	$\sim 10^{12}$ G	$\sim 10^{9}$ G
Spindown luminosity ($\dot{E}$)	$\sim 10^{32}$ erg s^{-1}	$\sim 10^{26}$ erg s^{-1}
Polar cap potential drop ($\Phi_{\rm max}$)	$\sim 10^{12}$ V	$\sim 10^{10}$ V
γ-ray emission mechanism	curvature, resonant IC and non-resonant IC	non-resonant IC
Radius of the star (R)	$\sim 10^{6}$ cm	$\sim 10^{9}$ cm
Gap height ($h_{\rm gap}$)	$\sim (10^3 - 10^4)$ cm	$\sim (10^5 - 10^6)$ cm
Relative emission height (r_e/R)	$\sim (10 - 100)$	~ 1000

6 TWO POSSIBLE INTERPRETATIONS TO RRATS

Lately, a new type of transient pulsars are identified (McLaughlin et al 2006). The identification of their periods suggest that they are similar objects like normal pulsars. However, they are quiescent most of the time, and only become radio loud occasionally. These new objects are dubbed "Rotating RAdio Transients" or RRATs.

Based on the wisdom we gain from the above-mentioned studies, one has two immediate possible interpretations to RRATs (Zhang, Gil & Dyks 2006). The first interpretation is similar to the mechanism proposed to interpret the transient WDPSR GCRT J1745–3009 (Zhang & Gil 2005). In this interpretation, RRATs are neutron star pulsars slightly below the radio emission deathline (RS75; Zhang et al. 2000; Harding & Muslimov 2002). Magnetic activities in the polar cap region would occasionally trigger pair production, and hence, radio emission. The second idea is that these are just those normal pulsars with reversal radio emission components (Dyks et al. 2005b). Unlike normal pulsars whose main outward emission is detected, these pulsars have only reversed inward emission sweeps the line of sight. Intrinsically they are the same as normal pulsars, but they are the other half of the nulling pulsars, i.e. they are visible during a nulling pulsar "nulls" through reversing the emission direction. PSR B1822–09 is the special case that we see both sides of the emission (Dyks et al. 2005b). The two models predict different X-ray emission features, so that X-ray observations of RRATs would lead to the identification of the right mechanism, which in turn, sheds light on the radio emission problem.

7 FINAL WORDS

Recent new observations (e.g. hot, small polar caps; double pulsar system; peculiar bursting source GCRT J1745–3009; RRATs) as well as the new ideas of interpreting them (inward emission, emission direction reversal, transient white dwarf pulsar, etc) greatly broadened our traditional view of radio pulsars. These possible new clues would greatly help to understand the mysterious pulsar radio emission.

Acknowledgements I thank stimulative collaborations with J. Dyks, J. Gil, A. Loeb, G. G. Pavlov, D. Sanwal on various topics covered in this review. In particular, I'd like to thank Janusz Gil for delivering the talk on behalf of me at the conference. My research at UNLV is supported by NASA under grants NNG05GB67G, NNG05GH92G, and NNG05GH91G.

References

Becker, W., Trümper, J., 1997, A&A, 326, 682
Burgay, M. et al., 2004, Nature, 426, 521
Cheng, A. F., Ruderman, M., 1980, ApJ, 235, 576
Cheng, K. S., Gil, J., Zhang, L., 1998, ApJ, 493, L35
Deshpande, A. A., Rankin, J. M., 1999, ApJ, 524, 1008
Dyks, J., Frackowiak, M., Slowikowska, A. Rudak, B., Zhang, B., 2005a, ApJ, 633, 1101
Dyks, J., Zhang, B., Gil, J., 2005b, ApJ, 626, L45
Gil, J. et al., 1994, A&A, 282, 45

Gil, J., Melikidze, G. I., Geppert, U., 2003, A&A, 407, 315
Gil, J., Melikidze, G. I., Zhang, B., 2006a, A&A, 457, L5
Gil, J., Melikidze, G. I., Zhang, B., 2006b, ApJ, 650, 1048
Gil, J., Mitra, D., 2001, ApJ, 550, 383
Gil, J., Sendyk, M., 2000, ApJ, 541, 351
Harding, A. K., Muslimov, A. G., 2001, ApJ, 556, 987
Harding, A. K., Muslimov, A. G., 2002, ApJ, 568, 862
Hyman, S. D., et al., 2005, Nature, 434, 50
Kijak, J., Gil, J., 2003, A&A, 397, 969
Levinson, A., Melrose, D., Judge, A., Luo, Q., 2005, ApJ, 631, 456
Lyne, A., et al. 2004, Science, 303, 1153
Lyutikov, M., 2004, MNRAS, 353, 1095
Lyutikov, M., 2005, MNRAS, 362, 1078
Lyutikov, M., Blandford, R. D., Machabeli, G., 1999, MNRAS, 305, 338
McLaughlin, M. A., Rankin, J. M., 2004, MNRAS, 351, 808
McLaughlin, M. A. et al., 2006, Nature, 439, 817
Melrose, D. B., 1995, J. Astrophys. Astr., 16, 137
Melrose, D. B., 2004, In: F. Camilo and B. M. Gaensler, eds., IAU Symp. 218, Young Neutron Stars and Their Environments, San Francisco: ASP, p 349 (astro-ph/0308471)
Navarro, J., Manchester, R. N., 1996, ASPC, 105, 249
Navarro, J., Manchester, R. N., Sandhu, J. S. et al., 1997, ApJ, 486, 1019
Qiao, G. J., Lee, K. J., Wang, H. G., Xu, R. X., Han, J. L., 2004, ApJ, 606, L49
Rankin, J. M., & Rathnasree, N., 1997, J. Astrophys. Astr. 18, 91
Ruderman, M., Sutherland, P. G., 1975, ApJ, 196, 51
Spitkovsky, A., Arons, J., 2004, AAS HEAD Meeting #8, #08.02.
Turolla, R., Possenti, A., Treves, A., 2005, ApJ, 628, L49
Usov, V. V., Melrose, D. B., 1996, ApJ, 464, 306
Wright, G. A. E., 2004, MNRAS, 351, 813
Xu, R. X., Qiao, G. J., Zhang, B., 1999, ApJ, 522, L109
Xu, R. X., Zhang, B., Qiao, G. J., 2001, APh, 15, 101
Zhang, B., Gil, J., Dyke, J. 2007, MNRAS, 374, 1103
Zhang, B., Gil, J., 2005, 631, L143
Zhang, B., Harding, A. K., 2000, ApJ, 532, 1150
Zhang, B., Harding, A. K., Muslimov, A. G., 2000, ApJ, 531, L135
Zhang, B., Loeb, A., 2004, ApJ, 614, L53
Zhang, B., Sanwal, D., Pavlov, G. G., 2005, ApJ, 624, L109
Zhu, W. W., Xu, R. X., 2006, MNRAS, 365, L16