MFN= 007282
 01 SID/SCD
 02 5898
 03 INPE-5898-PRE/2042
 04 CEA
 05 S
 06 as
 10 Wu, X.
 10 Chian, Abraham Chian Long
 12 Temporal variation of pulsar dispersion measure
 14 261-264
 30 Astrophysical Journal
 31 443
 32 1 Part 1
 40 En
 41 En
 42 <E>
 58 DGE
 61 <PI>
 64 <1995>
 68 PRE
 76 GEOFISICA ESPACIAL
 83 A new theory is proposed to explain the temporal
 variation of the dispersion measure of pulsars. In view
 of the extremely high values of the observed radio
 luminosity, the pulsar radio waves in the vicinity of
 the source region within a pulsar magnetosphere obey a
 nonlinear dispersion relation which depends on the pulse
 amplitude. Hence the observed DM variations might be due
 to the influence of the pulse amplitude on the
 dispersion relation. It is shown that there is a
 correlation between the DM fluctuation and the radio
 luminosity, suggesting that the variations of the pulse
 intensity may be one of the important causes of DM
 fluctuations.
 88 PULSARS
 88 STARS
 88 DISPERSION MEASURE
 88 RADIO CONTINUM
 90 b
 91 FDB-19960404
 92 FDB-MLR

TEMPORAL VARIATION OF PULSAR DISPERSION MEASURE

XINJI WU^{1,2,3} AND ABRAHAM C.-L. CHIAN^{2,3}

Received 1993 July 7; accepted 1994 October 21

ABSTRACT

A new theory is proposed to explain the temporal variation of the dispersion measure of pulsars. In view of the extremely high values of the observed radio luminosity, the pulsar radio waves in the vicinity of the source region within a pulsar magnetosphere obey a nonlinear dispersion relation which depends on the pulse amplitude. Hence the observed DM variations might be due to the influence of the pulse amplitude on the dispersion relation. It is shown that there is a correlation between the DM fluctuation and the radio luminosity, suggesting that the variations of the pulse intensity may be one of the important causes of DM fluctuations.

Subject headings: pulsars: general — radio continuum: stars

1. INTRODUCTION

The dispersion measure (DM) is an important physical parameter obtainable from pulsar radio signals that provides the foundation of our knowledge about pulsar distance and the electron content of the galactic interstellar medium. There are increasing observational evidence of temporal variations of pulsar dispersion measure. In practice, DM is usually determined by "profile alignment," that is, by calculating the time delay between the average profile observed at a pair of widely separated frequencies and using the linear plasma dispersion relation to define the linear dispersion measure

$$(DM)_L = 2.41 \times 10^{-16} \frac{f_2 - f_1}{f_2^2 - f_1^2} = \int_0^d n_e dl. \quad (1)$$

The DM fluctuations were first noticed by Rankin & Roberts (1971) and Isaacman & Rankin (1977) in Crab pulsar, PSR 0531+21. The most prominent event being a 2 year rise from a nominal value of $56.7892 \text{ cm}^{-3} \text{ pc}$ to $56.8519 \text{ cm}^{-3} \text{ pc}$. Other measurements of DM fluctuations are obtained by Hamilton, Hall, & Costa (1985) for PSR 0833–45, by Rawley, Taylor, & Davis (1988), Cordes et al. (1990) for PSR 1937+21 and by Foster, Backer, & Wolszczan (1990) for PSR 1951+32. Recent observations given by Phillips & Wolszczan (1991) show that DM variations are present in the following six pulsars: PSR 0823+26, PSR 0834+06, PSR 0919+06, PSR 1133+16, PSR 1237+25, and PSR 1604–00. Rankin et al. (1970; Rankin & Counselman 1973) suggested that the Crab Nebula acts as a strong, variable screen and some part of the interstellar medium as a weak, steady screen. The DM variability of PSR 0531+21 has also been explained in terms of the variation in ionization produced in the nebula filament by varying soft X-ray flux of PSR 0531+21 (Apparao 1974). Several authors suggested that DM fluctuations are the result of the electron density irregularities in the interstellar medium drifting past the Earth-pulsar line of sight (Cronyn 1973;

Armstrong 1984; Cordes, Pidwerbetsky, & Lovelace 1986; Romani, Narayan, & Blandford 1986; Phillips & Wolszczan 1991).

In this paper, we propose a new theory to explain the DM variations of pulsars. In view of the extremely high values of the observed radio luminosity, the pulsar radio waves in the vicinity of the source region obey a nonlinear dispersion relation which depends on the pulse amplitude. Hence, the observed DM variations might be due to the influence of the pulse amplitude on the dispersion relation. We demonstrate that there is indeed a clear correlation between the DM fluctuation and the radio luminosity. The pulsar luminosity is variable on a wide range of time scales, which can be attributed to intrinsic luminosity fluctuations and/or to propagation effects through an inhomogeneous interstellar medium. Therefore, the DM variations might be the effects of the variations of the pulse intensity.

According to Stinebring & Condon (1990) and Kaspi & Stinebring (1992), the observed temporal variation of pulsar flux densities at radio frequencies can be attributed to either intrinsic luminosity fluctuations or propagation effects along the line of sight, or to some combination of both. Pulsars predicted to have extremely long refractive scintillation time scales are observed to have stable fluxes. Some authors concluded that most pulsars have intrinsically stable luminosity. However, it remains possible that DM has contributions from the pulsar environment such as nebula (Rankin et al. 1970; Rankin & Counselman 1973; Apparao 1974) or pulsar magnetosphere. It is the aim of this paper to explore the possibility that DM variations may receive contributions from the propagation effects within a pulsar magnetosphere.

The effects of wave propagation in pulsar magnetospheres have been considered previously by Melrose & Stoneham (1977), Melrose (1979), and Barnard & Arons (1986). Melrose & Stoneham (1977) and Melrose (1979) proposed that refraction in the pulsar magnetosphere can spatially separate radiation beams with two different polarization states in the low-density limit, thus account for the observed orthogonal modes. Their works were later generalized by Barnard & Arons (1986) into higher density regimes and refraction of ray trajectories in the open field line zone was examined. The results of these theoretical analyses suggest that propagation effects such as refraction in the pulsar magnetosphere may have important consequences for interpretation of pulsar radio

¹ Department of Geophysics, University of Peking, Beijing, and United Laboratory for Radio Astronomy, China.

² National Institute for Space Research-INPE, Sao Jose dos Campos, Brazil.

³ Department of Applied Mathematics and Theoretical Physics, University of Cambridge, UK.

data. In these previous studies, however, only linear propagation effects were treated. In the present paper, we focus attention on the nonlinear effects of wave propagation in the pulsar magnetosphere. For simplicity, we do not include the effect of ray refraction since ray tracing is based on linear principles and is not valid for nonlinear wave studies. Nonetheless, it would be interesting for future studies to investigate, the net effect of the magnetosphere, due to both nonlinearity and refraction, on the observed arrival time.

2. NONLINEAR MODEL OF DISPERSION MEASURE VARIATIONS

The high radio brightness temperature inferred from pulsar observations implies that the radio waves of pulsars are sufficiently strong to drive the magnetospheric charged particles to relativistic velocity (Bodo, Ferrari, & Massaglia 1981; Chian 1982; Chian & Kennel 1983; Chian 1992). The intensity of pulsar radio emission near the source region can be measured by a dimensionless, Lorentz-invariant, parameter

$$v = \frac{eE}{m_e \omega c} = 5.585 \frac{L^{1/2}}{nf\delta}, \quad (2)$$

where f = pulsar emission frequency in MHz, δ = size of emission region in 10^8 cm, n = index of refraction, and L = radio luminosity = $S \Delta f d^2$ (S = flux density, Δf = emission bandwidth, and d = distance to pulsar). The intensity parameter v varies with the radial distance r as

$$v(r) = v_s \frac{r_s}{r}, \quad (3)$$

where v_s is the value of v in the source region and r_s is the radial distance of the source region. When the relativistically strong pulsar radio waves leave the source region and travel through the pulsar magnetosphere, consisting of a streaming electron-positron plasma, they are governed by a nonlinear dispersion relation given by Max (1973), Clemmow (1974), Chian (1980).

$$n^2 = 1 - \frac{2\omega_p^2}{\gamma_s \gamma_v \omega^2}, \quad (4)$$

where $\gamma_v = (1 + v^2)^{1/2}$, $\gamma_s = (1 - V_s^2/c^2)^{-1/2}$ and V_s = plasma streaming velocity. Equation (4) is valid for either circular or linear wave polarizations (Clemmow 1974). For electron in a magnetic field of 10^{12} gauss, as expected near the pole, the cyclotron frequency, $\omega_b = eB/\gamma_s mc$, is higher than plasma frequency, ω_p . However, the radio emission from most pulsars originates at a height about 10^8 cm, with exception of some short-period pulsars. Here the field is reduced to about 10^6 gauss, and secondary particles with $\gamma \simeq 10^3$ would have cyclotron frequency less than plasma frequency. The ω_b falls as r^{-3} , but the ω_p falls as $r^{-3/2}$. In the region from emission location to light cylinder, $\omega_s^2 \ll \omega_p^2$ for pulsars with long period and the effect of magnetic field can be neglected, with exception of some short-period pulsars. For example, for PSR 0823+16 the value of ω_b is less than that of ω_p at height of emission region. In practice, it is convenient to express the proper plasma frequency, $\omega_p/\gamma_s^{1/2}$, in equation (4) in terms of measurable pulsar parameters in the observer's frame of reference, which according to the Sturrock-Ruderman-Sutherland model (Manchester & Taylor 1977) is

$$\frac{\omega_p}{\gamma_s^{1/2}} = \left(\frac{8e\gamma_p \Omega B_0}{m_e c} \right)^{1/2} \left(\frac{R}{r} \right)^{3/2}, \quad (5)$$

where γ_p = Lorentz factor of primary particles, Ω = angular rotation frequency of pulsar, B_0 = magnetic field at the neutron star surface, and R = neutron star radius. The wave frequency emitted by the coherent curvature radiation is

$$\omega_c = \gamma_s^3 \frac{3c}{2\rho}, \quad (6)$$

where ρ is the radius of curvature of the open field lines, $\rho = 10^9$ cm at distance greater than 10^6 cm above the stellar surface. Since significant coherent radiation can only be emitted when ω_c exceeds ω_p , the height of emission region must satisfy the condition

$$r_s \geq \left(\frac{8e\gamma_p \Omega B_0}{m_e c} \right)^{1/3} R \omega^{-2/3}. \quad (7)$$

The region wherein nonlinear dispersion is operative defines a strong, thin screen located between the source region and the light cylinder. The dispersion contribution of this thin screen is obtained by combining equations (2), (4), and (5), which yields the following formula of nonlinear dispersion measure:

$$\begin{aligned} (\text{DM})_{NL} &= 2.41 \times 10^{16} \frac{e\gamma_p \Omega B_0 R^3}{\pi^2 c^2 m_e} I \\ &= 2.58 \times 10^5 \Omega B_0 I \text{ (cm}^{-3} \text{ pc)}, \end{aligned} \quad (8)$$

with

$$\begin{aligned} I &= \int_{r_s}^{r_c} \left\{ dr \left[r^3 \left(1 + v_s^2 \frac{r_s^2}{r^2} \right)^{1/2} \right] \right\} \\ &= \frac{(v_s^2 + 1)^{1/2}}{v_s^2 r_s^2} - \left\{ \left[v_s^2 + \left(\frac{r_s}{r} \right)^2 \right]^{1/2} / (v_s^2 r_s r_c) \right\}, \end{aligned} \quad (9)$$

where r_c is the radial position of the light cylinder. The total dispersion measure is the sum of the nonlinear dispersion measure due to the thin screen plus the usual linear dispersion measure due to the interstellar medium, namely

$$(\text{DM})_{\text{TOTAL}} = (\text{DM})_{NL} + (\text{DM})_L. \quad (10)$$

The contribution of nonlinear dispersion measure is proportional to Ω and B_0 . The variations of DM are determined by I . It is important to note that $(\text{DM})_{NL}$ is a function of the parameters v_s as shown by equation (9) and v_s is a function of the radio luminosity L as shown in equation (2). Hence, our theory predicts that DM variations are related to L variation.

3. COMPARISON WITH OBSERVATION

The pulsar radio luminosity is variable on a wide range of timescales from microseconds to years. Variations on shorter or longer timescales have been shown to be at least partly extrinsic, caused for example by diffractive or refractive interstellar scintillation (Cordes et al. 1986; Romani et al. 1986; Kaspi & Stinebring 1992; Stinebring & Condon 1990). The question remains, if there is also an intrinsic component? Kaspi & Stinebring (1992) pointed out that the observed timescales for long-term flux variation for seven pulsars are in good agreement with refractive scintillation theory. Four pulsars, including the Vela pulsar, have observed timescales that are in poor agreement with theoretical predictions. Stinebring et al. (1984) demonstrated that the long-term stability of polariza-

tion waveforms has been questioned but day-to-day fluctuations of waveforms obtained at similar pointing position are small. The only disadvantage that waveforms have as alignment diagnostics is that they are not constant in flux density, since intrinsic pulsar fluctuations and interstellar scintillations cause variation in the flux density scale. For PSR 0531+21, the intensity at 408 MHz increased by a factor of 4 over a period 3 months at the end of 1974 (Lyne & Thorne 1975). This may yet be attributed to refractive focusing. But the long time-scale does not fit the theory at present (Lyne & Smith 1990). Isaacman & Rankin (1977) suggested that for Crab pulsar, the Crab Nebula acts as a strong, variable screen and some part of the interstellar medium as a weak, steady one. For this explanation, the effect of ISM is not important. It is reasonable that the role of magnetosphere can be important. PSR 0531+21 not only has large radio luminosity but also variations of luminosity. Even if the variations are partially attributed to pulsar itself, the DM will be varying according to our model.

The conclusion is that the variability in observed flux densities of compact radio sources can be produced by intrinsic luminosity changes and/or by propagation effects along the line of sight. Although recent studies of flux density variations on long timescales by Stinebring & Condon (1990) and Kaspi & Stinebring (1992) are in agreement with the refractive scintillation, but in the introduction of their papers, they mention that there is also the possibility of intrinsic variations of pulsar luminosity.

We plot in Figures 1 and 2 the variation of the rms DM fluctuations (σ_{DM}) and the maximum DM fluctuations $[(\Delta DM)_{max}]$ as a function of the radio luminosity L , for nine and six pulsars, respectively. The data of σ_{DM} and $(\Delta DM)_{max}$ derive from the data of 1971 to 1974 listed in Table 3 of Isaacman & Rankin (1977) for PSR 0531+21, from the data of Figure 1 of Rawley et al. (1988) for PSR 1937+21 (since 1984 October to 1987 January), and from Phillips & Wolszczan

FIG. 1.—Rms dispersion measure fluctuation vs. radio luminosity for nine pulsars. The points are labeled as follows: (1) PSR 0531+21; (2) PSR 0919+06; (3) PSR 0834+06; (4) PSR 1237+25; (5) PSR 0823+26; (6) PSR 1604-00; (7) PSR 1133+16; (8) PSR 0950+08; (9) PSR 1937+21. The error bars represent the uncertainty in the computed rms due to DM measurement errors given by Phillips & Wolszczan (1991). The best-fit line corresponds to a scaling $\sigma_{DM} \propto L^{0.49}$.

FIG. 2.—Maximum DM fluctuation vs. luminosity for six pulsars. The points are labeled as follows: (1) PSR 0531+21; (2) PSR 0919+06; (3) PSR 0823+26; (4) PSR 1937+214; (5) PSR 0834+06; (6) PSR 1604-00. The best-fit line corresponds to a scaling $(\Delta DM)_{max} \propto L^{0.41}$.

(1991) for the rest of the pulsars. The Vela pulsar also shows DM variations, predominantly a linear variation with time over the 15 years (Hamilton et al. 1985). The Vela pulsar has large value of DM fluctuations and large value of radio luminosity, which is in agreement with our model. We do not include this pulsar, because there are only five data during 15 years in the paper of Hamilton et al. (1985) and there are much more data of DM for those pulsars in Figures 1 and 2 during 2-3 years.

Evidently, Figures 1 and 2 indicate that there is good correlations of σ_{DM} - L and $(\Delta DM)_{max}$ - L . This renders strong support for the argument that the DM fluctuations are related to the radio luminosity. For PSR 0531+21, the radio pulse-to-pulse variations are the largest, which is an observational evidence that pulsars with larger L also have larger L fluctuations.

Phillips & Wolszczan (1991) plotted the rms DM fluctuation (σ_{DM}) versus dispersion measure and found that the size of the DM fluctuations were correlated with the dispersion measure and concluded that the density fluctuations were interstellar. Generally, the pulsar at larger distance must necessarily have larger luminosity and larger DM. So the Figures 1 and 12 of Phillips & Wolszczan (1991) may reflect on the same fact. But, there is an important pulsar, PSR 1937+214, with the largest DM (70.040) compared with the sample of Phillips & Wolszczan. If density fluctuations were attributed solely to the ISM, then the DM fluctuations of PSR 1937+214 must be larger than those pulsars in Figure 12 of Phillips & Wolszczan (1991), but the value of σ_{DM} of PSR 1937+214 is the smallest. When we plot PSR 1937+214 in this figure ($\log \sigma_{DM} - \log DM$), the relation becomes very poor. Certainly, there is a scaling coefficient that depends on the strength of electron density variations in the ISM. This scaling coefficient varies wildly from line of sight to line of sight. Therefore, the scatter in any plot of σ_{DM} versus DM reflects the nature of electron density variations along the different lines of sight. However, we can find that in Figure 1, PSR 1937+214 is in good agreement with the relation that the value of σ_{DM} increases with increasing luminosity.

FIG. 3.—Relation between $(DM)_{NL}$ and v_s for PSR 0823+26

We now compute the variation of $(DM)_{NL}$ with v_s for a typical pulsar, PSR 0823+26. The region of nonlinear dispersion (i.e., thin screen) is from r_s to r_c , where r_c is defined as the radial distance between the pulsar and the light cylinder along the observer's line of sight

$$r_c = \frac{R_c}{\sin(\alpha + \beta)}, \quad (11)$$

where $R_c = c/\Omega$ is the radius of light cylinder, α is the magnetic inclination, and β is the angle between the line of sight and the magnetic axis. The values of α and β can be estimated from the geometry investigations (Lyne & Manchester 1988; Wu & Xu 1992; Wu et al. 1986; Xu & Wu 1991; Kuzmin & Wu 1992). The values of α and β are 13.1 and 1.1 degree for the main pulse respectively (Lyne & Manchester 1988). Then we get $r_c \approx 10^{10}$ cm. Our calculations show that the region beyond the light cylinder has negligible contribution. The curve in Figure 3 shows the relation between $(DM)_{NL}$ and v_s for PSR 0823+26 computed from the formula of nonlinear dispersion measure equation (8). The values of $(DM)_{NL}$ increase with decreasing values of v_s in a wide range values of v_s (0.25–100). The value of

v_s can be estimated from equation (2). For PSR 0823+26, $v_s \approx 10$. The observed value of $(\Delta DM)_{max}$ is $0.0027 \text{ cm}^{-3} \text{ pc}$ and $\sigma_{DM} = 0.00033$ which can be explained by a few times variation of luminosity L .

4. CONCLUSIONS

1. There may be multiple contributions for the DM fluctuations. The DM fluctuations may originate from a high-density region occupying a small fraction of the total line of sight, either the pulsar nebula (Isaacman & Rankin 1977; Rankin et al. 1970; Rankin & Counselman 1973; Apparao 1974) or the magnetosphere of pulsar (as suggested in this paper). Alternatively, DM fluctuations may result from electron density irregularities in the interstellar medium drifting past the Earth-pulsar line of sight (Cronyn 1973; Armstrong 1984; Cordes et al. 1986; Romani et al. 1986; Phillips & Wolszczan 1991). We think that both kinds of explanation are reasonable. These two processes may coexist for a given pulsar or one of them may be dominant for some pulsars. Hence, we suggest that DM variation may arise from the combined effects of pulsar magnetosphere + nebula + interstellar medium.

2. The nonlinear dispersion model of this paper suggests that the DM variations are caused by the variation of radio luminosity and the $(DM)_{NL}$ is proportional to Ω and B_0 . So the pulsars with short period and strong magnetic field strength may have larger $(DM)_{NL}$. The simultaneous measurement of DM and intensity of mean pulse is called for to verify this theoretical prediction.

3. Arrival time measurements of pulsar radio pulses have provided the basis for obtaining precise information on the binary motion of several pulsars (Manchester et al. 1991; Hulse & Taylor 1974) as well as search for planetary systems around pulsars (Rasio et al. 1992; Barles, Lyne, & Shemar 1991; Wolszczan & Frail 1992). Since the arrival time depends on the wave dispersion in the pulsar magnetosphere or interstellar medium corrections may be required for timing observations of pulsars. Therefore, further observational and theoretical investigations on the origins of DM variations are essential for achieving accurate timing measurements.

The authors are grateful to FAPESP of Brazil, NSF of China and National Climbing Program of China for financial support and DAMTP-University of Cambridge for hospitality.

REFERENCES

- Apparao, K. M. V. 1974, *Ap&SS*, 31, L9
 Argyle, E., & Gower, J. F. R. 1972, *ApJ*, 175, L89
 Armstrong, J. W. 1984, *Nature*, 307, 527
 Barnard, J. J., & Arons, J. 1986, *ApJ*, 302, 138
 Barles, M., Lyne, A. G., & Shemar, S. L. 1991, *Nature*, 352, 311
 Bodo, G., Ferrari, A., & Massaglia, S. 1981, *Ap&SS*, 80, 261
 Chian, A. C.-L. 1980, *Lett. Nuov. Cimento*, 29, 393
 ———. 1982, *A&A*, 112, 391
 ———. 1992 in *IAU Colloq. 128, Magnetospheric Structure and Emission Mechanisms of Radio Pulsars*, ed. T. H. Hankins, J. M. Rankin, & J. Gil (Zielona: Univ. Zielona Gora Press), 365
 Chian, A. C.-L., & Kennel, C. F. 1983, *Ap&SS*, 97, 9
 Clemmow, P. C. 1974, *J. Plasma Phys.*, 12, 287
 Cordes, J. M., Pidwerbetsky, A., & Lovelace, R. V. E. 1986, *ApJ*, 310, 737
 Cordes, J. M., Wolszczan, A., Dewey, R. J., Blaskiewicz, M., & Stinebring, D. R. 1990, *ApJ*, 349, 245
 Cronyn, W. 1973, *BAAS*, 5, 407
 Foster, R. S., Backer, D. C., & Wolszczan A. 1990, *ApJ*, 356, 243
 Hamilton, P. A., Hall, P. J., & Costa, M. E. 1985, *MNRAS*, 214, 5
 Hulse, R. A., & Taylor, J. H. 1974, *ApJ*, 195, L51
 Isaacman, R., & Rankin, J. M. 1977, *ApJ*, 214, 214
 Kaspi, V. M., & Stinebring, D. R. 1992, *ApJ*, 392, 530
 Kuzmin, A. D., & Wu, X. J. 1992, *Ap&SS*, 190, 209
 Lyne, A. G., & Manchester, R. N. 1988, *MNRAS*, 234, 477
 Lyne, A. G., & Smith, F. G. 1990, *Pulsar Astronomy* (Cambridge: Cambridge Univ. Press)
- Lyne, A. G., & Thorne, D. J. 1975, *MNRAS*, 172, 197
 Manchester, R. N., Lyne, A. G., Robinson, C., D'Amico, N., Bailes, M., & Lim, J. 1991, *Nature*, 352, 219
 Manchester, R. N., & Taylor, J. H. 1977, *Pulsars* (San Francisco: Freeman)
 Max, C. E. 1973, *Phys. Fluids*, 16, 1277
 Melrose, D. B. 1979, *Australian J. Phys.*, 32, 61
 Melrose, D. B., & Stoneham, R. J. 1977, *Proc. Astron. Soc. Australia*, 3, 120
 Phillips, J. A., & Wolszczan, A. 1991, *ApJ*, 382, L27
 Rankin, J. M., Comell, J. M., Craft, H. D., Richards, D. W., Campbell, D. M., & Counselman, C. C. III. 1970, *ApJ*, 162, 707
 Rankin, J. M., & Counselman, C. C. III. 1973, *ApJ*, 181, 875
 Rankin, J. M., & Roberts, J. A. 1971, in *IAU Symp. 46, The Crab Nebula*, ed. R. D. Davies & F. G. Smith, 114
 Rasio, F. A., Nicholson, P. D., Shapiro, S. L., & Tenkolsky, S. A. 1992, *Nature*, 355, 325
 Rawley, L. A., Taylor, J. H., & Davis, M. N. 1988, *ApJ*, 326, 947
 Romani, R. W., Narayan, R., & Blandford, R. 1986, *MNRAS*, 220, 19
 Stinebring, D. R., & Condon, J. J. 1990, *ApJ*, 352, 207
 Stinebring, D. R., Cordes, J. M., Rankin, J. M., Weisberg, J. M., & Boriakoff, V. 1984, *ApJS*, 55, 247
 Wolszczan, A., & Frail, D. A. 1992, *Nature*, 355, 145
 Wu, X. J., & Xu, W. 1992, in *IAU Colloq. 128, Magnetospheric Structure and Emission Mechanisms of Radio Pulsars*, ed. T. H. Hankins, J. M. Rankin, & J. Gil (Zielona: Univ. Zielona Gora Press), 400
 Wu, X. J., Qiao, G. J., Xia, X. Y., & Li, F. 1986, *Ap&SS*, 119, 101
 Xu, W., & Wu, X. J. 1991, *ApJ*, 380, 550