The Astrophysical Journal, 519:L81–L84, 1999 July 1

# ARE THERE PLANETS AROUND THE PULSAR PSR B0329+54?

Maciej Konacki,[1] Wojciech Lewandowski,[1] Alex Wolszczan,[1,2] Oleg Doroshenko,[3] and Michael Kramer[4]

*Received 1999 January 25; accepted 1999 April 27; published 1999 May 14*

## ABSTRACT

Using the pulse arrival time measurements of the pulsar PSR B0329+54 made between 1994 and 1998 with the 100 m Effelsberg and the 32 m Toruń radio telescopes supplemented with the archival JPL data, we demonstrate that the planets suggested to orbit this $\sim 5 \times 10^6$ yr old object are unlikely to be real. The previously proposed timing models, including 3 and 16.8 yr orbits of terrestrial-mass planets, fail to predict the pulse arrival times at later epochs. If this pulsar has planetary companions, the remaining possibilities include low-mass objects that are below the current detection threshold, multiple terrestrial-mass planets in orbits whose superposition could produce the timing noiselike effects, and any planets with orbital periods significantly exceeding the 30 yr data span. However, it is likely that the observed variations in timing residuals of PSR B0329+54 are caused by spin irregularities that are intrinsic to this relatively young neutron star.

*Subject headings:* planetary systems — pulsars: general — pulsars: individual (PSR B0329+54)

## 1. INTRODUCTION

The first planets orbiting a star other than the Sun have been discovered around a 6.2 ms pulsar, PSR B1257+12 (Wolszczan & Frail 1992; Wolszczan 1994). This pulsar belongs to a variety of old, rapidly rotating neutron stars generally believed to be spun up by accretion from their binary stellar companions (Phinney & Kulkarni 1994 and references therein). Consequently, scenarios of planet formation around the millisecond pulsars exploit the various possibilities to transform a circumpulsar matter left over from binary evolution into planet-mass bodies (Phinney & Hansen 1993; Podsiadlowski 1993).

In the case of younger, slower spinning solitary pulsars, a possibility for planetary companions is more difficult to envision. Such planets, assuming that they could form around a massive, rapidly evolving star, would have to either survive this evolutionary process, including the final supernova explosion, or be created from supernova “fallback” material (Thorsett & Dewey 1993; Lin, Woosley, & Bodenheimer 1991).

The currently very meager statistics of planet detections around neutron stars (see Wolszczan 1997 for a recent review) emphasize the importance of long-term timing measurements of large samples of both the millisecond period and the slower “normal” pulsars in providing better constraints for theories of pulsar planet formation. One of the recently initiated pulsar timing projects designed to address this problem is the program of long-term, weekly timing measurements of ~100 normal pulsars with the 32 m radio telescope of the Toruń Centre for Astronomy (TCfA) of the Nicolaus Copernicus University in Toruń, Poland.

Included in the TCfA program is the well-known, bright, 0.714 s pulsar PSR B0329+54 that has been one of the very few neutron stars long suspected to possess planetary-mass companions. Demiański & Prószyński (1979) were the first to suggest that the apparent 3 yr periodicity in the pulse arrival times for this pulsar, measured with the NRAO/FCRAO telescopes, could be a manifestation of the orbital motion of a terrestrial-mass planet. This periodicity was not seen by Cordes & Downs (1985) in an extended set of the timing data from the same source, but it was reclaimed by Bailes, Lyne, & Shemar (1993), who have detected it in the data acquired with the 76 m Jodrell Bank radio telescope. Most recently, Shabanova (1995) has reanalyzed the JPL data collected over 13 years by Downs & Reichley (1983) at 2380 MHz using the NASA Deep Space Network facility together with her own timing measurements made at 102.7 MHz with the Pushchino BSA transit array. The conclusion of this analysis was that, with the existence of a 3 yr periodicity in the PSR B0329+54 timing residuals remaining unclear, there is a 16.8 yr period in the data that can best be accounted for by invoking a terrestrial-mass planet in a significantly eccentric orbit around the pulsar.

In this Letter, we revisit the PSR B0329+54 planets issue using the timing measurements of this pulsar made with the 32 m TCfA antenna since mid-1996. Supplementing these data with the earlier results from the 100 m Effelsberg telescope and combining them with the published JPL observations, we show that the previously reported 3 and 16.8 yr modulations of pulse arrival times from PSR B0329+54 no longer exist. We suggest that the observed ephemeral periodicities represent manifestations of the processes that are intrinsic to this neutron star.

## 2. OBSERVATIONS

Timing measurements of PSR B0329+54 with the 32 m TCfA telescope were made with a 1.4/1.7 GHz dual-channel, cooled receiver, typically tuned to frequencies around 1.7 GHz. The left and right circularly polarized signals were mixed down to 150 MHz and fed into a 2 × 64 × 3 MHz–channel pulsar processor (the Penn State Pulsar Machine 2, hereafter PSPM-2). After detection, the dual-channel signals were added together, 4 bit quantized, and passed to the data acquisition computer for pulse averaging synchronously with the Doppler-shifted pulsar period. The 10 minute averaged pulse profiles were time-tagged using the hydrogen-maser station clock and stored for further analysis. These observations have been part of a pulsar timing program with the 32 m TCfA telescope that began in 1996 July and currently involves weekly measurements of ~100 strong pulsars. During the initial 6 months of

---

[1] Toruń Centre for Astronomy, Nicolaus Copernicus University, ul. Gagarina 11, Toruń, PL-87-100, Poland; kmc@astri.uni.torun.pl, boe@astro.uni.torun.pl.

[2] Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802; alex@astro.psu.edu.

[3] Astro-space Center, PN Lebedev Physical Institute, Leninskij Prospect, 53, Moscow, 117924, Russia; olegd@psun32.prao.psn.ru.

[4] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, Bonn, D-53121, Germany; michael@mpifr-bonn.mpg.de.

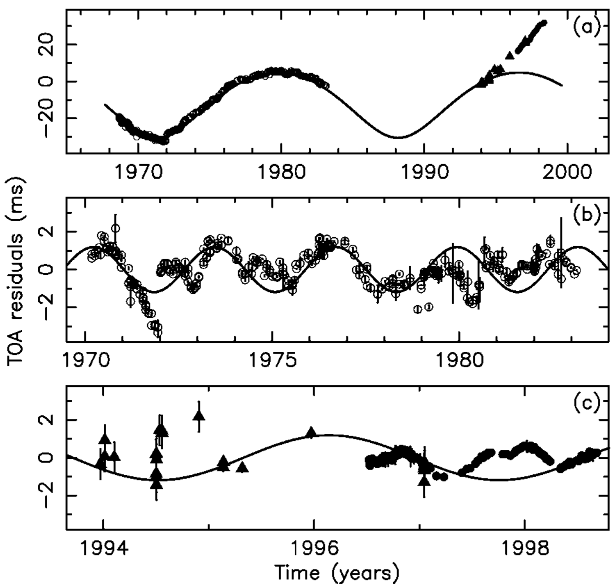

FIG. 1.—Postfit residuals for the timing analysis of the TOAs of pulses from PSR B0329+54. The JPL, Effelsberg, and TCfA data points are marked with open circles, filled triangles, and filled circles, respectively. The solid lines denote the theoretical residual variation for timing models, including a 16.8 yr planet and a 3 yr planet around the pulsar. (*a*) Residuals for a 2 $M_\oplus$ planet in a 16.8 yr orbit, as proposed by Shabanova (1995) on the basis of the archival JPL observations (1969–1983) and the Pushchino measurements until 1995 (not available). Residuals from the 1994–1998 TOA measurements at Effelsberg and TCfA clearly deviate from this model. (*b*) The JPL residuals for a 0.3 $M_\oplus$ planet in a 3 yr orbit originally suggested by Demiański & Prószyński (1979) with the longer term TOA variations fitted out. The overplotted theoretical residual curve, based on a 3 yr planet model derived from the 1970–1979 data, emphasizes a deterioration of this periodicity after 1979. (*c*) A continuation of (*b*) for the Effelsberg and TCfA residuals with a theoretical orbital phase preserved over the 1983–1994 gap in the data. The absence of a 3 yr periodicity in the residuals is evident.

this project, PSR B0329+54 had been timed daily along with a few other of the brightest objects.

Observations with the 100 m Effelsberg radio telescope were made at several frequencies between 1.4 and 43 GHz beginning in 1993 December using the Effelsberg Pulsar Observing System as described in Kramer et al. (1997, 1998). Time-tagging of 15 s pulse integrations was provided by a hydrogen-maser clock calibrated with the signals from the Global Positioning System of satellites and a latched microsecond counter. Dedispersed pulse profiles were integrated for 15 s during the data acquisition. For timing purposes, pulse profiles integrated over 5–10 minutes were formed in the off-line analysis process.

## 3. TIMING ANALYSIS

The topocentric times of arrival (TOAs) of pulses from PSR B0329+54 were calculated by cross-correlating the observed integrated profiles with a high signal-to-noise ratio template. The topocentric TOAs were then referred to the solar system barycenter using the JPL DE200 ephemeris. Barycentric TOAs from the JPL measurements made between 1968 and 1983 were taken from the literature (Downs & Reichley 1983).

The timing models examined in this Letter had astrometric parameters fixed at values taken from Taylor, Manchester, & Lyne (1993). A constant offset between the TCfA and Effelsberg TOAs was removed from the global fits of timing models to the combined TOA measurements with the two telescopes. An unknown offset between the TCfA/Effelsberg data set and the JPL TOAs from earlier epochs was taken into account in a manner that is explained below. The least-squares fits of the timing models to the data were performed with the timing analysis package TEMPO[5] (Taylor & Weisberg 1989).

The results of our analysis of the TOA measurements for PSR B0329+54 are summarized in Figure 1. To verify the possibility of a 16.8 yr planet around this pulsar, timing residuals were calculated using the model of Shabanova (1995) with the planet excluded. Theoretical residuals for a planet with Shabanova's orbital parameters (Table 1) were compared with observations as illustrated in Figure 1*a*. Since the amount of a constant offset between the JPL TOAs and the combined TOAs from Effelsberg and TCfA was not known, the latter data set was shifted so that the earliest available Effelsberg residual lined up with that predicted for the planetary timing model. Evidently, the behavior of timing residuals from TOAs measured after 1993 does not follow the prediction based on planetary ephemerides suggested by Shabanova (1995).

To analyze a 3 yr periodicity in the TOA residuals from PSR B0329+54 reported by Demiański & Prószyński (1979) and Bailes et al. (1993), we performed a fit of this model to the JPL data spanning a period from 1970 through 1979. As shown in Table 1, the best-fit parameters derived in this manner are insignificantly different from those published by Demiański & Prószyński. Our analysis shows that, after 1979, a marginal 3 yr periodicity that was visible earlier has gradually disappeared (Fig. 1*b*). This fact has been noticed by Shabanova (1995) in the same set of JPL TOAs as well as in her own partially overlapping Pushchino measurements. Residuals based on a hypothetical orbit of a 3 yr planet derived from our analysis, including the most recent Effelsberg and TCfA measurements, are shown in Figures 1*b* and 1*c* with the orbital phase maintained over the 11 yr period between 1983 and 1994. To make this comparison possible, period derivatives up to the fourth-order derivative have been fitted out of the entire data set in order to eliminate large-amplitude, long-term variations in TOA residuals exhibited by PSR B0329+54 over a range

TABLE 1

ORBITAL PARAMETERS FOR PUTATIVE PLANETS AROUND B0329+54

| PARAMETER | 3 YEAR "PLANET"<br>Demiański & Prószyński 1979 | <br>This Letter | 17 YEAR "PLANET"<br>(Shabanova 1995) |
|---|---|---|---|
| Semimajor axis (ms) .............. | 1.201 (142) | 1.18 (7) | 17.7 (4) |
| Eccentricity ......................... | 0.0 | 0.0 | 0.23 (2) |
| Epoch of periastron (MJD) ......... | 41139 (30) | 40965 (17) | 41056.5 (60.0) |
| Orbital period (days) ............... | 1105 (25) | 1181 (12) | 6160 (60) |
| Longitude of periastron (deg) ...... | ... | ... | 269 (3) |

NOTE.—The figures in parentheses are 1 $\sigma$ uncertainties in the last digits quoted.

---

[5] The most recent version is available at http://pulsar.princeton.edu/tempo, which is maintained and distributed by Princeton University and the Australia Telescope National Facility.

of timescales. It is quite clear, especially in the well-sampled TCfA data, that the putative 3 yr planet is absent from the TOA measurements made between 1994 and 1998. This is entirely consistent with the loss of coherence by this marginal periodicity in the JPL/Pushchino TOAs measured between 1983 and 1995 as reported by Shabanova (1995). Moreover, this result does not confirm the continued existence of the 3 yr TOA oscillation in PSR B0329+54 claimed by Bailes et al. (1993) on the basis of Jodrell Bank measurements made until 1992.

## 4. DISCUSSION

Our analysis of the behavior of possible 3 and 16.8 yr periodicities, postulated to exist in the TOAs from PSR B0329+54, clearly shows that they have disappeared over a 11 yr period between 1983 and 1994 and are no longer present in the data recently acquired with the TCfA and Effelsberg radio telescopes. In fact, as mentioned above, the Pushchino observations by Shabanova (1995), which cover most of that period, indicate that the 3 yr periodicity had already begun to dissolve in 1979. Consequently, we are led to believe that the existing experimental evidence does not support the previously suggested presence of two planet-mass bodies on 3 and 16.8 yr orbits around this pulsar.

The case of PSR B0329+54 discussed here provides an excellent illustration of the difficulties involved in searching for TOA periodicities, possibly induced by planetary dynamics, in the presence of intrinsic phenomena that may cause similar TOA variations. In principle, free precession of a neutron star can manifest itself in the form of a cyclic pulse timing behavior through pulse shape variations, geometric beam wobble, and induced torque fluctuations (e.g., Cordes 1993). Nelson, Finn, & Wasserman (1990) have demonstrated that, under suitable circumstances, a distinction between precessional effects and TOA periodicities caused by planetary dynamics may be difficult to make.

As shown in Figure 1, PSR B0329+54 exhibits TOA residual variations ranging from a few months to many years. These timescales and occasional cyclic appearances of TOA residuals are similar to the TOA variations seen in a handful of objects, such as the Crab pulsar (Lyne, Pritchard, & Graham-Smith 1993), the Vela pulsar, and PSR B1642−03 (Cordes 1993). Although it is tempting to hypothesize that this type of timing behavior could be caused by free precession, it should be noted that such long-term precessional modes would be impossible to generate in the presence of a perfect superfluid vortex pinning to the crust of a neutron star (Shaham 1977). In fact, the most recent work by Sedrakian, Wasserman, & Cordes (1998) indicates that precessional effects cannot account for the cyclic timing residuals observed in some pulsars and that other kinds of neutron star spin irregularities have to be considered to explain them.

Another example of TOA variations that may exhibit a cyclic appearance is the timing noise known to characterize normal, young pulsars (e.g., Lyne 1992). This effect has been shown to correlate with the spin-down rate (Dewey & Cordes 1989; Arzoumanian et al. 1994), and it finds a natural explanation in terms of the irregularities in the angular momentum transfer between the fluid interior and the crust of a spinning-down neutron star. Phenomenologically, the timing noise is best described in terms of random walk processes that lead to pulse-phase fluctuations characterized by “red” power spectra (Boynton et al. 1972; Groth 1975). Consequently, slow, occasionally cyclic variations in the pulse timing residuals, if not monitored over sufficiently long periods of time, can be mistakenly identified as strictly periodic phenomena.

Assuming that the TOA variations observed in PSR B0329+54 are due to the pulsar’s timing activity, we have quantified it in terms of a parameter defined by Arzoumanian et al. (1994) as

$$\Delta(t) = \log\left(\frac{1}{6\nu}\,|\ddot{\nu}|\,t^3\right), \tag{1}$$

where $\ddot{\nu}$ is the second-order time derivative of the pulsar spin frequency $\nu$, $t$ is the reference time interval, and $\Delta(t)$ itself has the simple meaning of a pulsar clock error over the reference time period. Its empirical form, established by these authors for $t = 10^8$ s, $\Delta(t = 10^8\ \mathrm{s}) = 6.6 + 0.6 \log \dot{P}$, predicts $\Delta = -2.2$ for PSR B0329+54, in good agreement with $\Delta_{\rm JPL} = -2.1$ (an average of four $10^8$ s intervals) and $\Delta_{\rm TCfA} = -1.5$, given a large scatter of the $\Delta$ measurements for other pulsars. This result demonstrates that the TOA behavior of PSR B0329+54 can be consistently explained in terms of a timing noise generated by the neutron star seismology.

In addition to the absence of the previously suggested 3 and 16.8 yr orbit planets around PSR B0329+54 discussed above, further constraints on possible planetary companions to this pulsar can be placed in a following manner. For a circular, “edge-on” orbit, and a pulsar mass of 1.4 $M_\odot$, the amplitude of timing residuals due to planetary motion is

$$\tau_{\rm pl} = 1.2\left(\frac{M_{\rm pl}}{M_\oplus}\right)P_{\rm orb}^{2/3}, \tag{2}$$

where $\tau_{\rm pl}$ is in milliseconds, $M_{\rm pl}$ and $M_\oplus$ are the masses of the pulsar planet and the Earth, respectively, and $P_{\rm orb}$ is the orbital period in years. This relationship is shown in Figure 2 for the JPL and TCfA residuals, with and without the removal of any long-term TOA fluctuations parameterized in terms of higher order derivatives of the pulsar’s spin frequency. Although the limits based on the existing data allow a detection of both the Jovian-mass and terrestrial-mass planets around PSR B0329+54 over a wide range of orbital periods, none are evident in the timing residuals. In principle, this could occur, if multiple planets contributed to the observed residuals with a combination of periods, amplitudes, and phases producing a timing noiselike effect. The remaining possibilities include low-mass planets (lower than the mass of Mars) that are below the current detection threshold and planets with orbital periods longer than the available data span (∼30 yr).

With the exception of the confirmed case of a planetary system around PSR B1257+12 (Wolszczan 1994) and the convincing evidence for a giant planet-mass body in orbit around a binary millisecond pulsar, PSR B1620−26 in the globular cluster M4 (Thorsett et al. 1999), no other neutron star planet has been detected so far. In particular, recent timing results on newly discovered millisecond pulsars (Bailes et al. 1997; Bell et al. 1997) do not indicate the presence of any planetary-mass companions to these objects. Likewise, none of the published data from the completed and ongoing timing programs of the normal, slow pulsars that are similar to PSR B0329+54 suggest the presence of planets around any of these objects (Thorsett, Phillips, & Cordes 1993; Bailes et al. 1993).

The existence of planets around neutron stars like PSR B0329+54 depends on the conditions of their survival while orbiting massive ($\geq$6–8 $M_\odot$), rapidly evolving pulsar progenitor stars. Moreover, any surviving planets must face the challenge posed by the supernova explosions of their parent stars. Generally, as discussed by Thorsett & Dewey (1993), the existence of planets around normal pulsars that are given an extreme environment created by the evolution of massive stars, although not entirely implausible, may be difficult to envision. Fortunately, long-term timing measurements at several observatories have been continued, and new projects, such as the Effelsberg and TCfA timing programs, have been initiated in the last few years. Consequently, with the growing time span of these measurements and the increasing number of pulsars observed, the odds for establishing usable constraints on the possible origins of neutron star planets will be steadily improving.

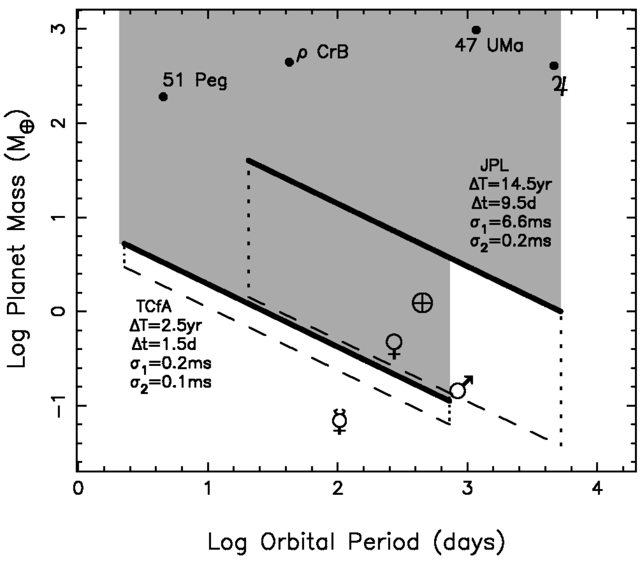

FIG. 2.—Planetary detection limits from the timing measurements of PSR B1257+12 at JPL and TCfA. The orbital parameter space (*shaded area*) is limited by detection thresholds (*solid lines*) defined by the data span, $\Delta T$, the average time interval between consecutive observations, $\Delta t$, and the measured timing noise, $\sigma_1$. The dashed lines mark the detection thresholds determined by TOA measurement noise, $\sigma_2$, after the removal of long-term TOA fluctuations. The locations of the four inner planets of the solar system, Jupiter, and three representative extrasolar planets are shown for comparison purposes.

M. Konacki and W. L. were supported by KBN grant 2.PO3D.028.08. A. W. acknowledges partial support from NASA grant NAG5-4301 and NSF grant AST 96-19552. The PSPM-2 project was supported by the KBN grant 2.P304.003.05 to M. Demiański and J. Gil, the KBN grant 2.PO3D.028.08 to A. W., and the TCfA funds. The PSPM-2 has been constructed at the Penn State's Center for Electronic Design, Communications, and Computing. Major contributions to the design and testing of the PSPM-2 by S. Anderson, B. Cadwell, and B. Jacoby are gratefully acknowledged. We also thank A. Kus and the TCfA technical staff for help with the PSPM-2 installation at the 32 m radio telescope and M. Redmerska and G. Feiler for assistance with the observations.

## REFERENCES

Arzoumanian, Z., Nice, D. J., Taylor, J. H., & Thorsett, S. E. 1994, ApJ, 422, 671
Bailes, M., et al. 1997, ApJ, 481, 386
Bailes, M., Lyne, A. G., & Shemar, S. L. 1993, in ASP Conf. Ser. 36, Planets around Pulsars, ed. J. A. Phillips, S. E. Thorsett, & S. R. Kulkarni (San Francisco: ASP), 19
Bell, J. F., Bailes, M., Manchester, R. N., Lyne, A. G., Camilo, F., & Sandhu, J. S. 1997, MNRAS, 286, 463
Boynton, P. E., et al. 1972, ApJ, 175, 217
Cordes, J. M. 1993, in ASP Conf. Ser. 36, Planets around Pulsars, ed. J. A. Phillips, S. E. Thorsett, & S. R. Kulkarni (San Francisco: ASP), 43
Cordes, J. M., & Downs, G. S. 1985, ApJS, 59, 343
Demiański, M., & Proszyński, M. 1979, Nature, 282, 383
Dewey, R., & Cordes, J. M. 1989, in NATO/ASI Ser. C, Timing Neutron Stars, ed. H. Ogelman & E. P. J. van den Heuvel (Dordrecht: Kluwer), 119
Downs, G. S., & Reichley, P. E. 1983, ApJS, 53, 169
Groth, E. J. 1975, ApJS, 29, 431
Kramer, M., Xilouris, K. M., Jessner, A., Lorimer, D. R., Wielebinski, R., & Lyne, A. G. 1997, A&A, 322, 846
Kramer, M., Xilouris, K. M., Lorimer, D. R., Doroshenko, O., Jessner, A., Wielebinski, R., Wolszczan, A., & Camilo, F. 1998, ApJ, 501, 270
Lin, D. N. C., Woosley, S. E., & Bodenheimer, P. H. 1991, Nature, 353, 827
Lyne, A. G. 1992, Philos. Trans. R. Soc. London A, 341, 29
Lyne, A. G., Pritchard, R., & Graham-Smith, F. 1993, MNRAS, 265, L1003
Nelson, R., Finn, S., & Wasserman, I. 1990, ApJ, 348, 226
Phinney, E. S., & Hansen, B. M. S. 1993, in ASP Conf. Ser. 36, Planets around Pulsars, ed. J. A. Phillips, S. E. Thorsett, & S. R. Kulkarni (San Francisco: ASP), 371
Phinney, E. S., & Kulkarni, S. R. 1994, ARA&A, 32, 591
Podsiadlowski, P. 1993, in ASP Conf. Ser. 36, Planets around Pulsars, ed. J. A. Phillips, S. E. Thorsett, & S. R. Kulkarni (San Francisco: ASP), 149
Sedrakian, A., Wasserman, I., & Cordes, J. M. 1998, preprint (astro-ph/9801188)
Shabanova, T. V. 1995, ApJ, 453, 779
Shaham, J. 1977, ApJ, 214, 251
Taylor, J. H., Manchester, R. N., & Lyne, A. G. 1993, ApJS, 88, 529
Taylor, J. H., & Weisberg, J. M. 1989, ApJ, 345, 434
Thorsett, S. E., Arzoumanian, Z., Camilo, F., & Lyne, A. G. 1999, preprint (astro-ph/9903227)
Thorsett, S. E., & Dewey, R. J. 1993, ApJ, 419, L65
Thorsett, S. E., Phillips, J. A., & Cordes, J. M. 1993, in ASP Conf. Ser. 36, Planets around Pulsars, ed. J. A. Phillips, S. E. Thorsett, & S. R. Kulkarni (San Francisco: ASP), 31
Wolszczan, A. 1994, Science, 264, 538
———. 1997, Celest. Mech., 68, 13
Wolszczan, A., & Frail, D. A. 1992, Nature, 355, 145