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Detecting Planets Around Pulsars

Abstract

We review the results of searches for planet-mass bodies around neutron stars using the pulse timing technique. The precision of pulsar timing allows a detection of terrestrial-mass bodies orbiting slow pulsars and asteroidal-mass companions to millisecond pulsars. A planetary and asteroidal "noise" may be a precision-limiting factor in other uses of the pulse timing method. At present, PSR B1257+12, the 6.2-millisecond pulsar, remains the only neutron star accompanied by confirmed planets. There is a possibility for a fourth distant planet in this system.

I Introduction

The first planets beyond the Solar System have been detected around a billion year old neutron star, a 6.2-millisecond radio pulsar, PSR B1257+12 (Wolszczan & Frail 1992; Wolszczan 1994). The three companions to PSR B1257+12 remain the only known system of terrestrial mass planets orbiting a star other than the Sun. More recent results include growing evidence for a Jupiter-mass object orbiting a binary pulsar, PSR B1620−26, in the globular cluster M4 (Arzoumanian et al. 1996; Thorsett & Arzoumanian, these proceedings) and a possibility for an Earth-mass body around PSR B0329+54 (Shabanova 1995). The existence of pulsar planets, and a series of spectacular discoveries of giant planetary-mass objects around solar-type stars (e.g., Mayor & Queloz 1995; Marcy & Butler 1996; see Bos 1996 for a recent review) provide compelling evidence that extrasolar planetary systems can exist in a surprising, entirely unanticipated multitude of forms.

Radio pulsars, especially those of the millisecond period variety, are extremely stable rotators (see Phinney & Kulkarni 1994 for a recent review). The intrinsic rotational stability of these objects and the corresponding steady repetition rate of the observed pulses of radio emission makes them the most precise "cosmic clocks" known, with performance rivaling that of the best terrestrial time standards. Searches for extrasolar planets are the latest of the many applications of the pulsar clocks as probes of a wide range of astrophysical phenomena (e.g., Blandford 1992).

In this paper, we present the pulse timing as a high-precision method of detection of planetary mass bodies around neutron stars and summarize the results of searches for pulsar planets using this technique.

II Planets and pulse timing precision

Accurate measurements of the pulse time-of-arrival (TOA) variations generated by reflex motion of a pulsar due to orbiting planets provide a powerful method of the indirect planet detection. This method is closely related to single-line Doppler spectroscopy and astrometry which are widely used in planetary searches around ordinary stars. For a circular orbit and the pulsar mass, $M_{\rm psr} = 1.35\ {\rm M}_\odot$, a relationship between the planetary mass, m_2, the planet's orbital period, P_b, and the semi-amplitude, Δt, of the corresponding TOA variations is:

$$m_2 \sin i = 21.3 {\rm M}_\oplus \left(\frac{\Delta t}{1\,{\rm ms}}\right) \left(\frac{P_b}{1\,{\rm day}}\right)^{-2/3}, \tag{1}$$

where ${\rm M}_\oplus$ is the Earth mass, i is the orbital inclination and $m_2 \ll M_{\rm psr}$.

A practical demonstration of the consequences of this relationship is presented in Figure 1 which shows timing residuals from simulated observations of the Solar System planets with the Sun replaced by a 1.35 ${\rm M}_\odot$ neutron star. Clearly, the Jovian planets generate large residuals, the terrestrial planets are detectable with $a \leq 1$ ms precision provided by "normal," slowly rotating pulsars ($P \sim 1$ s) and they are extremely easy to recognize with millisecond pulsars due to their microsecond timing accuracy. Moreover, as demonstrated in Figure 1c, with a sub-microsecond timing precision attainable with the best pulsar clocks, the largest asteroids become barely detectable as well! In fact, this raises a disturbing possibility that the timing noise generated by circumpulsar asteroids may be one of the elements of the pulsar "weather" which delimit a precision of the TOA measurements.

It is illuminating to compare a planet detection power of the pulsar timing with the current capabilities of optical methods. Radial velocity precision required to detect a Moon-like body in an inner planet orbit around a solar-mass star would be ~ 1 mm s^{-1}. This corresponds to a timing residual amplitude of a few microseconds (Eq. 1) which is measurable with millisecond pulsars (e.g., Wolszczan 1994). The most advanced Doppler searches for planets around normal stars have recently achieved a ≤ 5 m s^{-1} accuracy (Butler et al. 1996) which is sufficient to detect Jupiters and "super-Jupiters." Further technical improvements may make it possible to lower this limit to ~ 1 m s^{-1} and gain access to Saturn-mass bodies. Undoubtedly, in a foreseeable future, the pulse timing method will remain unique in its ability to detect low-mass planetary objects outside the Solar System and to study their dynamics.

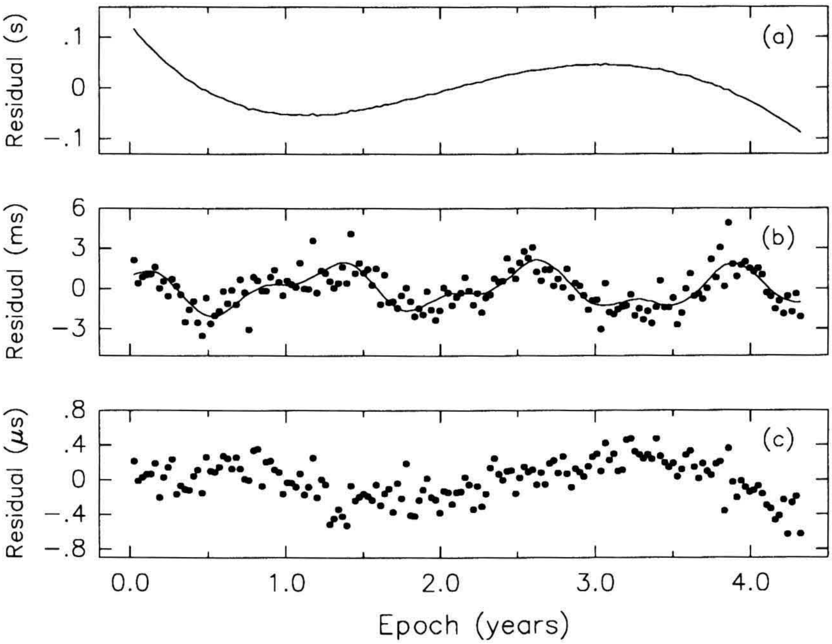

Figure 1. Simulated timing residuals from observations of the Solar System planets around a 1.4 $M_\odot$ pulsar, after subtraction of the best-fit model including the initial phase, the pulsar rotation period, P, and its slowdown rate, $\dot{P}$. *(a)* All planets present, the residuals are dominated by Jupiter. *(b)* Outer planets fitted out, the residuals for a slow pulsar (filled circles, timing accuracy 0.5 ms) show the presence of the Earth and Venus. The solid line represents the same detection with a slow pulsar replaced with a millisecond pulsar (0.1 μs timing precision). *(c)* All planets removed, the residuals from a millisecond pulsar (defined as above) reveal the presence of Ceres, the largest asteroid.

III Methods of pulsar planet detection

Practical methods of detection of the TOA variations caused by orbiting planets include direct fits of Keplerian and real orbits (e.g., Thorsett & Phillips 1992; Wolszczan 1994; Lazio & Cordes 1995) and model-independent frequency domain approaches based on Fourier transform techniques (Konacki & Maciejewski 1996; Bell et al. 1997). In fact, it appears that it is best to search for periodicities in TOAs (or residuals) by examining periodograms of the data and then refine the search by fitting orbits in time domain using the initial orbital parameters derived from frequency domain analysis. The Lomb-Scargle algorithm (Lomb 1976; Scargle 1982) provides an efficient way to compute spectra of unevenly spaced data.

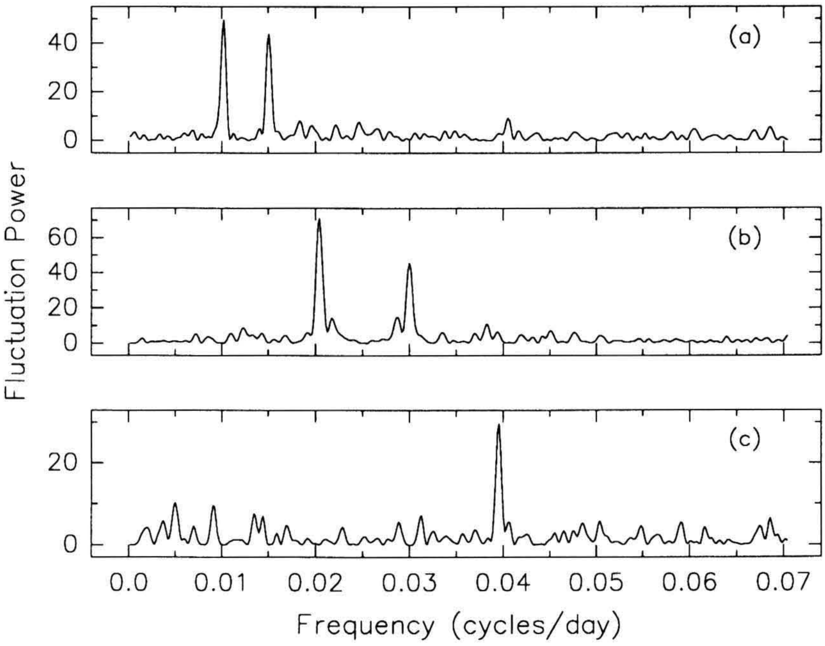

Figure 2. An example of the frequency domain analysis of pulse arrival times from the planet pulsar, PSR B1257+12, observed with the Arecibo telescope at 430 MHz. *(a)* A periodogram of the original TOA set, the two spectral peaks correspond to the orbits of planets B and C. *(b)* A periodogram of TOA variations with the fundamental frequencies of planets B and C removed, the peaks are first harmonics due to non-zero eccentricities of the orbits. *(c)* The fundamental frequencies and their first harmonics removed, a periodicity due to planet A becomes clearly visible (courtesy of M. Konacki).

This combination of methods has been successfully applied by Wolszczan & Frail (1992) and Wolszczan (1994) to detect planets around PSR B1257+12. Further refinements include a promising implementation of the frequency domain analysis in which contributions from any periodic TOA variations are successively subtracted from the data to reveal lower level fluctuations (Konacki & Maciejewski 1996; Figure 2).

IV Planets around PSR B1257+12

A 6.2 millisecond pulsar, PSR B1257+12, was discovered in 1990 during a pulsar search conducted with the 305 m Arecibo radiotelescope (Wolszczan 1991). The analysis of the follow-up timing observations of this pulsar has led to a detection of the first extrasolar planetary system (Wolszczan & Frail 1992) later confirmed by a detection of planetary perturbations between planets B and C (Wolszczan 1994). The

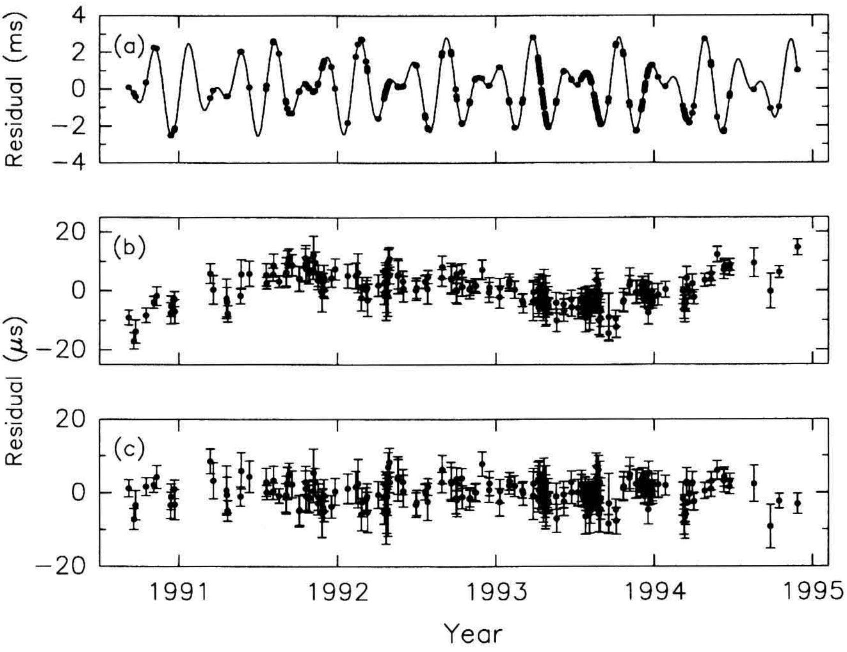

Figure 3. Timing residuals for PSR B1257+12 at 430 MHz. *(a)* A fit for the spin parameters and astrometric parameters only. *(b)* A fit including standard pulsar parameters, three planets and perturbations between planets B and C. *(c)* A fit with the second period derivative taken into account.

system consists of three planet-mass bodies, A, B, and C, with orbital characteristics listed in Table 1. Timing residuals due to planets B and C are shown in Figure 3a (planet A is not discernible on this scale).

Residuals from the least-squares fit of a model including the spin parameters and astrometric parameters of the pulsar, three orbits, and planetary perturbations are shown in Figure 3b. Clearly, the three-planet timing model for PSR B1257+12 requires a fit for a second-order derivative of the pulsar spin period, $\ddot{P}$, to remove unmodeled slow variations in the timing residuals (Figure 3c). A very intriguing possibility is that the observed $\ddot{P}$ is due to a dynamical influence of a distant, long-period fourth planet in the pulsar system (Wolszczan 1996).

As discussed in detail by Joshi & Rasio (1997), one can establish analytical relationships between the measured pulsar spin frequency derivatives and orbital elements of an outer planet, and use them to constrain its orbit in a straightforward manner. For PSR B1257+12, numerical values of the spin frequency and its first three derivatives are: $f = 160.8$ Hz, $\dot{f} = -8.6 \times 10^{-16}$, $\ddot{f} = (-1.25 \pm 0.05) \times 10^{-25}$, and $\dddot{f} = (1.1 \pm 0.3) \times 10^{-33}$, respectively.

Table 1: Parameters of the PSR B1257+12 planetary system.

	A	B	C
Keplerian orbital parameters			
Semi-major axis (light-ms)	0.0035(6)	1.3106(6)	1.4121(6)
Eccentricity	0.0	0.0182(9)	0.0264(9)
Epoch of periastron (JD)	2448754.3(7)	2448770.3(6)	2448784.4(6)
Orbital period (s)	2189645(4000)	5748713(90)	8486447(180)
Longitude of periastron (deg)	0.0	249(3)	106(2)
Parameters of the planetary system			
Planet mass ($M_\oplus$)	$0.015/\sin i_1$	$3.4/\sin i_2$	$2.8/\sin i_3$
Distance from the pulsar (AU)	0.19	0.36	0.47
Orbital period (days)	25.34	66.54	98.22

With the pulsar mass of 1.35 $M_\odot$, and the assumption that the observed $\dot{f}$ is dominated by the effect of orbital acceleration, these values of spin parameters give a planet in a $\sim$ 170 year orbit, with the orbital radius of $\sim$ 35 AU and the planetary mass of $\sim$ 95 $M_\oplus$, which would be a Saturn-mass object at a Pluto-like distance from the pulsar. Obviously, smaller acceleration contributions to $\dot{f}$ will lead to correspondingly different planetary masses and orbital elements. For example, a hypothetical fourth planet could have a low, Mars-like mass and orbit the pulsar at $\sim$ 9 AU (Joshi & Rasio 1997).

Another type of microsecond-level variability in the timing residuals of PSR B1257+12 is related to gravitational perturbations between planets B and C (e.g., Rasio et al. 1993; Malhotra 1993; Peale 1993). The detection of this effect in the timing residuals of PSR B1257+12 (Wolszczan 1994) has provided a final proof that the pulsar is indeed orbited by at least two planetary companions. The best-fit perturbation model constrains the minimum pulsar mass to be $\sim$ 1.2 $M_\odot$ and it implies that the masses of planets B and C must be similar to their respective "canonical", Earth-like values of 3.4 $M_\oplus$ and 2.8 $M_\oplus$ (Tab. 1). Another related dynamical constraint provided by the perturbation analysis is that inclinations of the planetary orbits are unlikely to be less than 60° for any reasonable choice of a neutron star mass.

V Planets around other pulsars

The discovery of planets around PSR B1257+12 has stimulated further searches for planetary companions to other neutron stars observable as radio pulsars. In addition to pulse timing measurements which allow a detection of isolated orbiting bodies, there

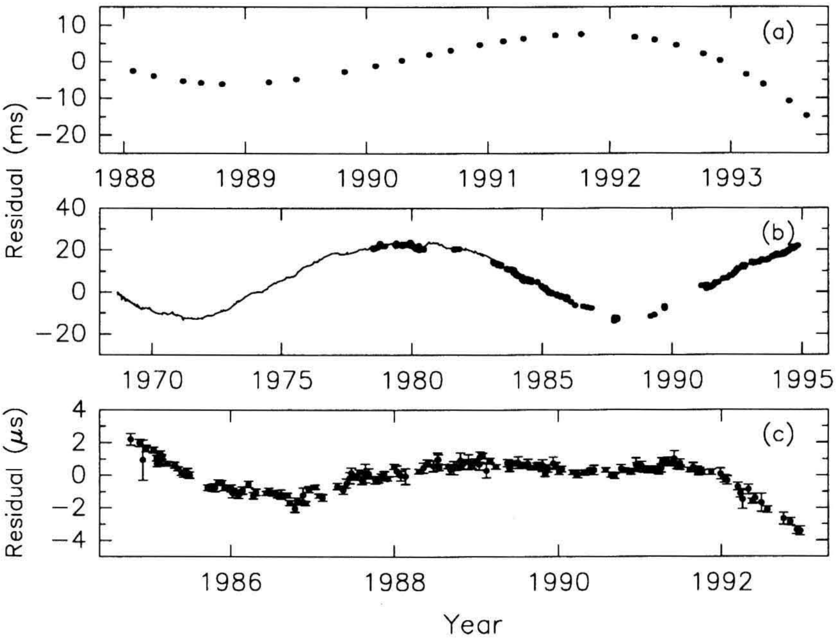

Figure 4. Long-term variations of pulse timing residuals for three pulsars. *(a)* PSR B1620−26 (courtesy of D. Backer), *(b)* combined JPL data (solid line) and Pushchino data (filled circles) for PSR B0329+54 (courtesy of V. Shabanova), and *(c)* PSR B1937+21 (Princeton public-access data base).

have been several attempts to make direct observations of possible debris disks around nearby pulsars (e.g., Zuckerman 1993; Phillips & Chandler 1993).

It is important to emphasize that there are a number of phenomena related to physics of the neutron star interiors and magnetospheres, the interstellar propagation, and the Solar System dynamics, which can affect pulse arrival times and are capable of mimicking planetary signatures in the timing residuals. In particular, a "timing noise" due to seismology of a neutron star and a precession-induced wobble of its rotation axis may lead to quasiperiodic TOA variations (see Cordes 1993 for an extensive review).

At the time of this writing, the best candidate for another planet pulsar is PSR B1620−26, the 11 ms pulsar in a 191 day neutron star-white dwarf binary system located in the globular cluster M4 (Arzoumanian et al. 1996, and references therein; Thorsett & Arzoumanian, these proceedings). The timing residuals for this pulsars (Figure 4a) show a deterministic, non-linear behavior that is most naturally accounted for by the presence of another orbiting mass around the inner binary. Arzoumanian et al. (1996) and Joshi and Rasio (1997) make a compelling case for a substellar (10^{-3}–10^{-2} $M_{\odot}$) companion, but they also demonstrate that a stellar mass object cannot be entirely ruled out.

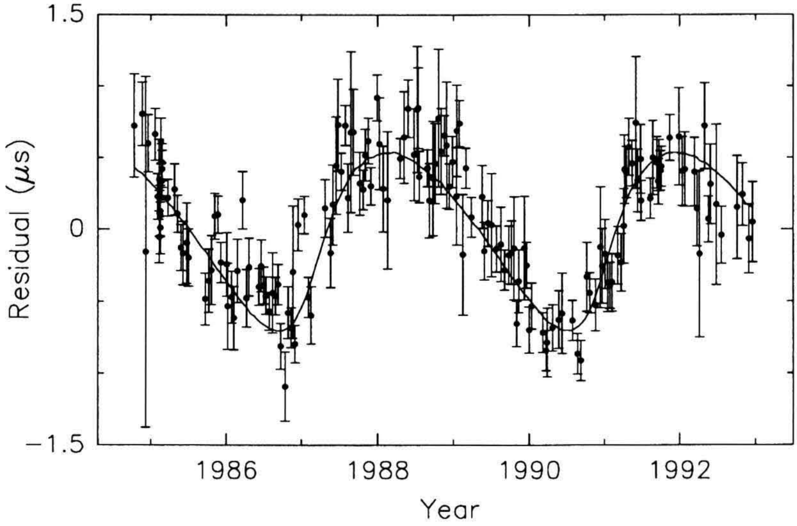

Figure 5. Timing residuals for PSR B1937+21 after subtraction of the standard model including the second order period derivative, $\ddot{P}$ (filled circles). The residual variation expected from a Ceres-mass asteroid in a 3.8 yr, 2.71 AU, eccentric orbit around the pulsar is denoted with the solid line (reproduced after Fukushima (1995), using the Princeton public-access data base).

A case for a terrestrial-mass planet around a relatively young, "slow" pulsar, PSR B0329+54, has been recently made by Shabanova (1995). Curiously, the first suggestion that this object can have a planetary companion has appeared as early as 1979. It was based on the detection of a $\sim$ 3 year periodicity in the timing residuals of the pulsar (Demiański & Prószynski 1979) later confirmed by Bailes, Lyne, & Shemar (1993). Shabanova's analysis suggests that the 3 year periodicity of residuals has practically disintegrated after 3–4 cycles, and that the data collected until 1995 are best explained in terms of a $\sim 2\ M_\oplus$ planet in a 17 year, eccentric orbit around the pulsar (Figure 4b). Of course, in view of a distinct possibility that other effects, most notably a timing noise, can contribute to the observed TOA behavior of PSR B0329+54, further long-term observations are necessary to either confirm or dismiss this intriguing case.

Another millisecond pulsar which has been considered as a possible candidate for planetary companions is the 1.57 ms pulsar, PSR B1937+21. This apparently isolated object has been shown by Kaspi, Taylor, & Ryba (1994) to exhibit microsecond-level, long-term TOA fluctuations (Figure 4c). In an unpublished analysis, Fukushima

(1995) has demonstrated that it is possible to remove these fluctuations by including a second-order period derivative and a 3.8 yr, eccentric orbit of a Ceres-mass asteroid in the timing model of this pulsar. To illustrate Fukushima's model, its reconstruction is shown in Figure 5. As in the case of PSR B0329+54 discussed above, a verification of this model will require many more TOA measurements and a much longer data span.

VI Discussion

At present, among more than thirty known millisecond pulsars, there are eight solitary objects that have either managed to dispose of their binary stellar companions, or they have been created without the aid of binary evolution (Bailes et al. 1997). If a missing stellar companion to the pulsar indicates a possibility of "leftover" planets around it, PSR B1257+12 remains the only confirmed case. Clearly, the pulsar planet formation is a low-efficiency process, but the available statistics are still insufficient to reliably constrain it.

The observed characteristics of PSR B1257+12 and its planets, when confronted with standard ideas concerning planetary formation (Levy 1993; Ruden 1993) and the origin and evolution of millisecond pulsars (Phinney & Kulkarni 1994), indicate that the planets have probably evolved in a circumpulsar disk of matter created from the remains of the pulsar's binary stellar companion. In addition, there is a large body of over 700 younger, "slow" pulsars, some of which may have retained planets of their parent stars (Thorsett & Dewey 1993).

Most of the scenarios of the millisecond pulsar planet formation concern themselves with possible ways to transform a fraction of the companion's mass into a protoplanetary disk, implying that the planets would subsequently form in a manner similar to that envisioned for the origin of planetary systems around normal stars (Podsiadlowski 1993; Phinney & Hansen 1993). One such scenario envisions that pulsar planets could be created as a by-product of a white dwarf merger which may produce a rapidly rotating neutron star and a suitable debris disk (Livio, Pringle & Saffer 1992). Another interesting alternative, described by Phinney & Hansen (1993), postulates a stellar companion disruption triggered by a close encounter with the pulsar formed in an asymmetric supernova explosion. This mechanism could produce a high-velocity single neutron star with a planetary system created from the remnants of the former binary companion. In this context, it is conceivable that the exceptionally high proper motion of PSR B1257+12 (~ 300 km s^{-1}) and the fact that this pulsar has planets are actually related.

One possible consequence of the existence of pulsar planets is that asteroid belts around neutron stars, if sufficiently common, may become a serious limiting factor of the pulse timing precision at submicrosecond levels. However, it is much more exciting to speculate that, even though the planetary systems around solar-type stars and pulsars are very likely to differ in their physical and chemical characteristics, the fundamental features of their dynamics should be similar. This possibility alone makes further searches for neutron star planets and the detailed studies of their dynamics with the pulse timing technique an important branch of astronomy of the extrasolar planets.

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References

Arzoumanian, A. et al. 1996, in Pulsars: Problems and Progress, IAU Coll. 160, ed. S. Johnston, M.A. Walker & M. Bailes (San Francisco: ASP), 525

Bailes, M., Lyne, A.G. & Shemar, S.L. 1993, in Planets around Pulsars, ed. J.A. Phillips, S.E. Thorsett & S.R. Kulkarni (San Francisco: ASP), 19

Bailes, M. et al. 1997, ApJ, 481, 386

Bell, J.F. et al. 1997, MNRAS, 286, 463

Blandford, R.D., 1992, Phil. Trans. R. Soc. Lond. A, 341, 177

Bos, A.P., 1996, Physics Today, 49, 32

Butler, R.P. et al. 1996, PASP, 108, 500

Cordes, J.M. 1993, in Planets around Pulsars, ed. J.A. Phillips, S.E. Thorsett & S. R. Kulkarni (San Francisco: ASP), 43

Demiański, M. & Prószyński, M. 1979, Nature, 282, 383

Joshi, K.J. & Rasio, F.A. 1997, ApJ, 479, 948

Kaspi, V.M., Taylor, J.H. & Ryba, M. 1994, ApJ, 428, 713

Konacki, M. & Maciejewski, A.J. 1996, Icarus, 122, 347

Lazio, T.J.W. & Cordes, J.M. 1995, Mercury, March/April, 23

Levy, E.H. 1993, in Planets around Pulsars, ed. J.A. Phillips, S.E. Thorsett & S.R. Kulkarni (San Francisco: ASP), 181

Livio, M., Pringle, J.E. & Saffer, R.A. 1992, MNRAS, 257, 15P

Lomb, N.R. 1976, Ap&SS, 39, 447

Malhotra, R. 1993, ApJ, 407, 266

Marcy, G.W. & Butler, R.P. 1996, ApJ, 464, L147

Mayor, M. & Queloz, D. 1995, Nature, 378, 355

Peale, S.J. 1993, AJ, 105, 1562

Phillips, J.A. & Chandler, C.J. 1993, ApJ, 420, L83

Phinney, E.S. & Hansen, B.M.S. 1993, in 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 Planets around Pulsars, ed. J.A. Phillips, S.E. Thorsett & S.R. Kulkarni (San Francisco: ASP), 149

Rasio, F.A. et al. 1993, in Planets around Pulsars, ed. J.A. Phillips, S.E. Thorsett &

S.R. Kulkarni, (San Francisco: ASP), 107
Ruden, S.P. 1993, in Planets around Pulsars, ed. J.A. Phillips, S.E. Thorsett & S.R. Kulkarni, (San Francisco: ASP), 197
Scargle, J.D. 1982, ApJ, 263, 835
Shabanova, T.W. 1995, ApJ, 453, 779
Thorsett, S.E. & Dewey, R.J. 1993, ApJ, 419, L65
Thorsett, S.E. & Phillips, J.A. 1992, ApJ, 387, L69
Wolszczan, A. 1991, Nature, 350, 688
Wolszczan, A. & Frail, D.A. 1992, Nature, 355. 145
Wolszczan, A. 1994, Science, 264, 538
Wolszczan, A. 1996, in Pulsars: Problems and Progress, IAU Coll. 160, ed. S. Johnston, M.A. Walker & M. Bailes (San Francisco: ASP), 91
Zuckerman, B. 1993, in Planets around Pulsars, ed. J.A. Phillips, S.E. Thorsett & S.R. Kulkarni (San Francisco: ASP), 303

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