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PLANETARY SYSTEMS AROUND NEUTRON STARS

*A research project supported by the
National Aeronautics and Space Administration*

A Summary of Research

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1 Introduction

This project was initiated in 1993, about one year after the announcement of two planets around PSR B1257+12. Its goal was to investigate planetary systems around neutron stars using high precision timing of radio pulsars as a tool. A microsecond precision of the pulse timing analysis, which is equivalent to a millimeter-per-second radial velocity resolution, makes it possible to detect asteroid-mass bodies in orbit around pulsars and to study the dynamics of pulsar planetary systems.

The project originally consisted of two long-term efforts: (i) routine observations and timing analysis of the millisecond pulsar PSR B1257+12 which was found to be orbited by at least two earth-mass bodies (Wolszczan and Frail 1992, *Nature*, **355**, 145) and (ii) a sensitive all-sky search for millisecond pulsars to detect further examples of neutron stars with planetary systems. In the third year of the project, it was expanded to include long-term timing observations of slow pulsars in search for planetary systems around these younger neutron stars.

The instrumentation used to conduct these investigations included the 305-m Arecibo antenna with the Penn State Pulsar Machine (PSPM-1), the 100-m Effelsberg telescope with the local pulse timing hardware, and the 32-m paraboloid of the Toruń Centre for Astronomy in Toruń, Poland (TCfA) with the PSPM-2, the second pulsar machine built at Penn State. The PI's collaborators included pulsar groups led by D. Backer (Berkeley), R. Foster (NRL), S. Kulkarni (Caltech), J. Taylor (Princeton) and R. Wielebinski (Bonn). One postdoc (Stuart Anderson), one graduate student (Brian Cadwell) and several undergraduates have been engaged in various aspects of research related to this project.

2 Summary of Accomplishments

The main results of our work on pulsar planets in the period covered by this report are described below.

- Two terrestrial-mass planets around the pulsar PSR B1257+12 have been confirmed through a detection of the predicted effect of mutual gravitational perturbations between these bodies (for details, see [3] and references therein). An inner, Moon-mass body in a 25-day, 0.19 AU orbit around the

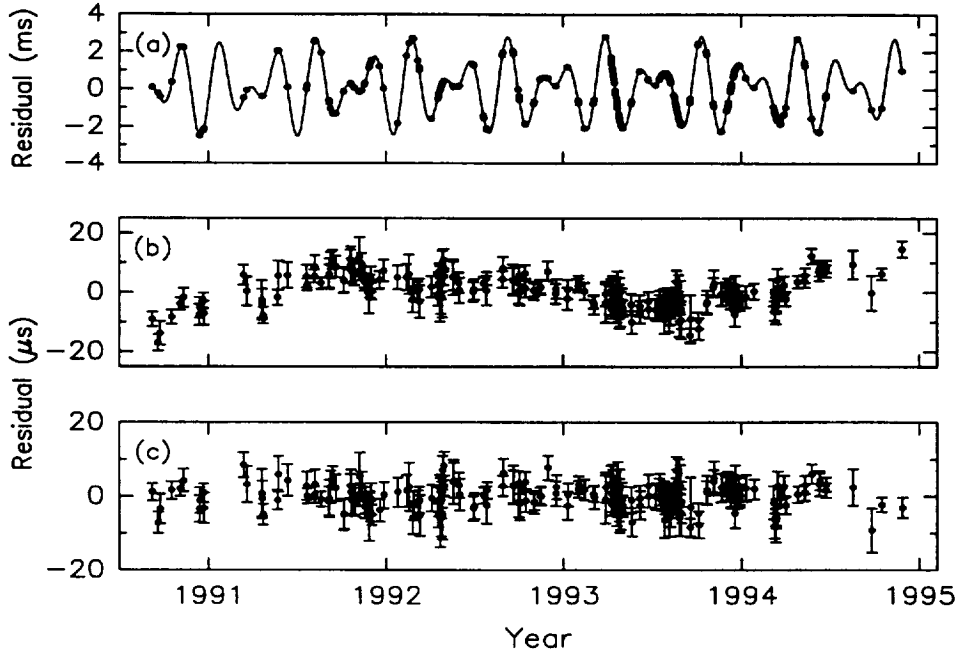


Figure 1: Timing residuals for PSR B1257+12 at 430 MHz. (a) A fit for the spin parameters and astrometric parameters reveals planets B and C. (b) A fit including standard pulsar parameters, three planets and perturbations between planets B and C still produces variations that may be due to a fourth, distant planet. (c) The residual variations in (b) are removed with a fit for the second period derivative.

pulsar has been detected. **These results represent the first confirmed detection of planets around a star other than the Sun.** The 1257+12 planets demonstrate that planetary systems around “exotic” objects such as neutron stars are possible and that studies of such planets and their dynamical characteristics are likely to be very beneficial to the global initiative of searching for extrasolar planetary systems. The existence of pulsar planets was commonly interpreted as a strong, new indication that planets around normal stars should not be uncommon, as confirmed later by discoveries of planetary companions to several Sun-like stars.

- A detailed analysis of the Arecibo timing data for PSR B1257+12 has revealed a new unmodelled effect remaining in the timing residuals after the

standard timing parameters, the three planets and planetary perturbations have been taken into account (Fig. 1b). This non-random timing behavior of the pulsar can be fully explained in terms of the presence of a Saturn-mass object in a 170-year orbit, about 30 AU away from the pulsar [11]. This intriguing result obviously requires further observational verification.

- Three new millisecond pulsars have been discovered with the Arecibo telescope. One of them, PSR J1640+22, is in a 175-day orbit with a low-mass stellar companion and has no detectable planets around it. The pulse timing data for the other two pulsars, PSR J1709+23 and PSR J1735+13, are still insufficient to confirm or rule out planets around these objects.

- A new, fast-sampled, 128-channel pulsar receiver (the Penn State Pulsar Machine, PSPM) has been built and installed at the Arecibo Observatory in 1994, with partial support from this grant. Compared to the performance of the existing Arecibo hardware, this new system has improved a timing precision of millisecond pulsars by a factor of 2-3 and it has dramatically increased the sensitivity of fast pulsar searches. The PSPM, which on the PI's initiative has become a "user-owned, public-access" hardware, has already contributed to several pulsar discoveries and will be an essential component of the future high-precision timing and survey programs at Arecibo.

- Millisecond pulsar timing with the 100-m Effelsberg telescope, initiated in 1994 is in progress. Data from this program have been used to bridge the gap in the Arecibo database caused by a 3-year unavailability of the telescope pointing due to the upgrade-related activities.

- Construction of a 64-channel pulsar receiver for the 32-m Toruń telescope has been completed at Penn State. This system has been installed in Toruń in 1996 and begun its service dedicated to long-term timing observations of a large body of "slow" pulsars in search for planetary companions. Partial support of this effort was provided by this grant.

- An educational impact of the detection and confirmation of pulsar planets cannot be overstated. The PI has been deeply engaged in a long-term effort to popularize these results and to meet the needs resulting from public interest, such as requests for materials or invitations to give popular talks in educational institutions. In collaboration with and financial help from Penn State and Cornell University, the PI has co-produced three videos and a number of visually attractive graphics explaining the nature and meaning of the planets detection. Pulsar planets have been among the most important scientific achievements in 1994 as seen by a number of popular science maga-

zines and received a 1994 “Best of What’s New” Grand Award of POPULAR SCIENCE.

3 Relevant Publications

1. Wolszczan, A., “PSR1257+12 and its Planetary Companions” 1993, *Planets Around Pulsars*, J. A. Phillips, S. E. Thorsett and S. R. Kulkarni (eds.), Publications of the Astronomical Society of the Pacific, p. 3.
2. Kaspi, V. M. and Wolszczan, A., “A Preliminary Analysis of Pulse Profile Stability in PSR1257+12” 1993, *Planets Around Pulsars*, J. A. Phillips, S. E. Thorsett and S. R. Kulkarni (eds.), Publications of the Astronomical Society of the Pacific, p. 81.
3. Wolszczan, A., “Confirmation of Earth–Mass Planets Orbiting the Millisecond Pulsar PSR B1257+12” 1994, *Science*, **264**, 538.
4. Wolszczan, A., “Toward Planets Around Neutron Stars” 1994, *Astrophys. Space. Sci.*, **212**, 67.
5. Wolszczan, A., “Probing Relativistic Gravity and Planetary Dynamics with Pulsar Clocks” 1994, *Proc. 26th Meeting of the Pol. Astron. Soc.*, M. J. Sarna and J. Zalewski (eds.), p. 70.
6. Wolszczan, A., “Planets Around Pulsars: A Progress Report” 1995, *Astrophys. Space. Sci.*, **223**, 205.
7. Wolszczan, A., “Pulsar Planets” 1995, *Millisecond Pulsars: A Decade of Surprise*, A. S. Fruchter, M. Tavani and D. C. Backer (eds.), Publications of the Astronomical Society of the Pacific, p. 377.
8. Wolszczan, A., “Planet” 1995, in *McGraw–Hill Yearbook of Science & Technology 1995*, New York: Mc Graw–Hill, p. 317.
9. Wolszczan, A., “Planets Around Pulsars” 1996, *Proc. IAU No. 165, “Compact Stars in Binaries”*, J. van Paradijs *et al.* (eds.), Dordrecht, Kluwer, p. 187.

10. Wolszczan, A., "Probing Planetary Dynamics with a Pulsar Clock" 1996, *Transactions of the IAU*, I. Appenzeller (ed.), vol. XXII B, p. 131.
11. Wolszczan, A., "Further Observations of the Planets Pulsar PSR B1257+12" 1996, *Proc. IAU No. 160, "Pulsars: Problems and Progress"*, S. Johnston et al. (eds.), ASP Conf. Ser. 105, 91.
12. Wolszczan, A., "Searches for Planets Around Neutron Stars" 1997, in *Proc. "Visual Double Stars: Formation, Dynamics and Evolutionary Tracks"*, J. A. Docobo et al. (eds.), Kluwer Academic Publishers, p. 221.
13. Wolszczan, A., "The Pulsar Planets Update" 1997, *Proc. "Planets Beyond the Solar System and the Next Generation of Space Missions"*, D. Soderblom (ed), ASP Conf. Ser. 119, 135.
14. Wolszczan, A., "Searches for Planets Around Neutron Stars" 1997, *Celestial Mechanics*, **68**, 13.
15. Wolszczan, A., "Detecting Planets Around Pulsars" 1997, in *Pulsar Timing, General Relativity, and the Internal Structure of Neutron Stars*, Proc. Coll. Royal Netherlands Academy of Arts and Sciences, Arzoumanian, A. and van den Heuvel, E. P. J. (eds.), in press.