Planets Around Neutron Stars

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Abstract. The most recent developments in the investigations of the known planets around two millisecond radio pulsars, PSR B1257+12 and PSR B1620-26, and in the searches for dusty disks around pulsars are discussed and related to relevant issues in astronomy of planets around normal stars. An unambiguous determination of masses and orbital inclinations of two of the three planets in the PSR B1257+12 system has been achieved by means of modeling their mean motion resonance condition. A direct detection of the white dwarf companion to PSR B1620-26 has resulted in new, tight constraints on the nature of a giant planet orbiting this binary system. An approximate coplanarity and a near 3:2 resonance of the orbits of the terrestrial-mass planets B and C around PSR B1257+12 strongly suggest a disk origin of this unique planetary system. The existence of a Jovian-mass planet around PSR B1620-26, in a metal-poor environment of the globular cluster M4, raises new questions concerning a relationship between stellar metallicity and the occurrence of planets around normal stars. The available upper limits on infrared emission from dust around pulsars do not exclude a possible existence of circumpulsar disks with masses reaching up to a few hundred $M_\oplus$.

1. Introduction

The most obvious connection between the discoveries of the first planetary system beyond the Sun orbiting a radio pulsar (Wolszczan and Frail, 1992) and the first planet around a Sun-like star (Mayor and Queloz, 1995) is the demonstration of a dramatic diversity of the extrasolar planets that would be difficult to anticipate without access to a direct observational evidence. This important point, which has remained perfectly valid over the 10-year period of extrasolar planet investigations, has been captured in the concluding remarks of the Nature discovery report on a planet around 51 Pegasi by Michel Mayor and Didier Queloz, who wrote: “From a complete planetary system detected around a pulsar, to the rather unexpected orbital parameters of 51 Peg b, searches begin to reveal the extraordinary diversity of possible planetary formation sites”.

The existence of planets around pulsars has consequences, whose significance cannot be overstated. First of all, such planets represent a truly intriguing astrophysical phenomenon which emphasizes a universal character of the planet formation process. Second, by creating planets in such an exotic environment (PSR B1257+12; Wolszczan, 1994) or moving them to it from elsewhere (PSR B1620-26; Sigurdsson et al., 2003), Nature offers us unique testing grounds for planet formation theories. This fortunate circumstance arises from the fact that a superb precision of the pulse timing method makes it possible to detect orbiting bodies as small as asteroids (Wolszczan, 1997) and study subtle dynamical effects such as gravitational perturbations between Earth-mass planets (Wolszczan, 1994) or a
microsecond-order contamination of the pulsar’s spin characteristics by a distant long-period planet (e.g. Thorsett et al., 1999). In principle, given enough time, one should be able to achieve a reasonably complete dynamical description of nearly any conceivable planetary system orbiting a neutron star that can be timed with a microsecond precision. Moreover, as terrestrial-mass planets around normal stars cannot be detected with the currently available observing methods, pulsar planets provide an unique tool to study low-mass components of the extrasolar planetary systems.

In this paper, we present the most recent results of the neutron star planets research and place them in a broader context of astronomy of the extrasolar planets. The relevant background information can be found in Wolszczan (1997) and Thorsett et al. (1999). In Section 2, we describe the measurements of masses and orbital inclinations of the PSR B1257+12 planets (Konacki and Wolszczan, 2003) and a study of the long-term stability of this planetary system (Goździewski et al., 2003). The recent results on the PSR B1620-26 triple system in the globular cluster M4 (Sigurdsson et al., 2003) are discussed in Section 3. Advances in searches for protoplanetary and debris disks around pulsars are summarized in Section 4. Finally, in Section 5 we discuss the current understanding of the pulsar planets and present our conclusions.

2. The PSR B1257+12 Planetary System

The 6.2-ms radio pulsar, PSR B1257+12, is orbited by three terrestrial-mass planets forming a compact system that is not much larger than the orbit of Mercury (Wolszczan, 1994). Relative sizes of the orbits and a distribution of masses of planets A, B, and C are strikingly similar to those of the three inner planets in the Solar System (Mazeh and Goldman, 1995). The updated parameters of the PSR B1257+12 planets have been recently published by Konacki and Wolszczan (2003) and are summarized in Table 1. Oscillations of the measured pulse arrival times caused by planets B and C are shown in Figure 1a.

The near 3:2 mean motion resonance (MMR) between planets B and C in the pulsar system and the existence of detectable gravitational perturbations between the two planets (Fig. 1b) (Rasio et al., 1992; Malhotra et al., 1992; Peale, 1993; Wolszczan, 1994; Konacki et al., 1999) provide the mechanism to derive their masses without an a priori knowledge of orbital inclinations. An approximate analytical model which includes the effect of gravitational interactions between planets B and C has been published by Malhotra (1993). Konacki et al. (2000) have developed a new semi-analytical model in which perturbations between the two planets are parametrized in terms of the two planetary masses and the mutual orientation of the orbits with a sufficient precision to make a practical application of this approach feasible. Using the simulated data, they have demonstrated that the planet masses and hence their orbital inclinations can be derived from a
Figure 1. The best-fit, daily-averaged TOA residuals for three timing models of PSR B1257+12 observed at 430 MHz. The solid line marks the predicted TOA variations for each timing model. (a) TOA residuals after the fit of the standard timing model without planets. TOA variations are dominated by the Keplerian orbital effects from planets B and C. (b) TOA residuals for the model including the Keplerian orbits of planets A, B and C. Residual variations are determined by perturbations between planets B and C. (c) Residuals for the model including all the standard pulsar parameters and the Keplerian and non-Keplerian orbital effects.

least-squares fit of this model to the pulse times-of-arrival (TOA) measurements spanning a sufficiently long period of time.

A practical application of this model to the PSR B1257+12 timing data collected with the Arecibo radiotelescope between 1991 and 2003 has been demonstrated by Konacki and Wolszczan (2003). A least-squares fit of the model to data gives the masses of planets B and C of $4.3 \pm 0.2 M_{\oplus}$ and $3.9 \pm 0.2 M_{\oplus}$, respectively, assuming the canonical pulsar mass, $M_{\text{psr}} = 1.4 M_{\odot}$. The timing residuals resulting from the best-fit of the perturbation model are shown in Figure 1c. Since the scatter in the known neutron star masses is small (Thorsett and Chakrabarty, 1999), it is unlikely that a possible error in the assumed pulsar mass would significantly affect these results. Because of the $\sin(i)$ ambiguity, there are four possible sets of the orbital inclinations for the planets B and C: $(53^\circ, 47^\circ)$, $(127^\circ, 133^\circ)$ corresponding to the difference in the ascending nodes $\Omega_C - \Omega_B \approx 0^\circ$ (relative inclination $I \approx 6^\circ$), and $(53^\circ, 133^\circ)$, $(127^\circ, 47^\circ)$, corresponding to the difference in the ascending nodes
Table I. Observed and derived parameters of the PSR B1257+12 planets.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planet A</th>
<th>Planet B</th>
<th>Planet C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projected semi-major axis, x (ms)</td>
<td>0.0030(1)</td>
<td>1.3106(1)</td>
<td>1.4134(2)</td>
</tr>
<tr>
<td>Eccentricity, e ................</td>
<td>0.0</td>
<td>0.0186(2)</td>
<td>0.0252(2)</td>
</tr>
<tr>
<td>Epoch of pericenter, T_p (MJD)</td>
<td>49765.1(2)</td>
<td>49768.1(1)</td>
<td>49766.5(1)</td>
</tr>
<tr>
<td>Orbital period, P_b (d) ........</td>
<td>25.262(3)</td>
<td>66.5419(1)</td>
<td>98.2114(2)</td>
</tr>
<tr>
<td>Longitude of pericenter, ω (deg)</td>
<td>0.0</td>
<td>250.4(6)</td>
<td>108.3(5)</td>
</tr>
<tr>
<td>Mass (M⊙) ....................</td>
<td>0.020(2)</td>
<td>4.3(2)</td>
<td>3.9(2)</td>
</tr>
<tr>
<td>Inclination, solution 1, i (deg)</td>
<td>...</td>
<td>53(4)</td>
<td>47(3)</td>
</tr>
<tr>
<td>Inclination, solution 2, i (deg)</td>
<td>...</td>
<td>127(4)</td>
<td>133(3)</td>
</tr>
<tr>
<td>Planet semi-major axis, a_p (AU)</td>
<td>0.19</td>
<td>0.36</td>
<td>0.46</td>
</tr>
</tbody>
</table>

\[ \Omega_C - \Omega_B \approx 180^\circ \] (relative inclination \( I \approx 174^\circ \)). Obviously, in both cases the planets have nearly coplanar orbits, but in the latter one, their orbital motions have opposite senses. Because our numerical simulations of the system’s dynamics show that this situation leads to distinctly different perturbative TOA variations that are not observed, only the first two sets of the orbital inclinations, 53°±4° and 47°±3° or 127° and 133° are plausible. This implies that the two planets move in nearly coplanar orbits in the same sense.

A precise knowledge of the initial condition of the PSR B1257+12 planetary system derived from the best-fit timing model makes it possible to investigate a dynamical stability of the system by means of a long-term numerical integration of the full equations of motion. Such an integration has been recently performed by Goździewski et al. (2003), who have detected no secular changes of the semi-major axes, eccentricities and inclinations of the planets over a 1 Gyr period. Variations of the orbital elements over the first 500,000 yr are shown in Figure 2. The most notable feature is the presence of a secular apsidal resonance (SAR) between the planets B and C with the center of libration about 180° (Fig. 2d). Curiously, the SAR has been recently found in several extrasolar planetary systems discovered by the radial velocity surveys (Ji et al., 2003). It remains to be established, whether a seemingly common occurrence of the SAR is significant or just coincidental.

In order to fully understand the dynamical stability of the PSR B1257+12 system, Goździewski et al. (2003) have investigated the structure of the phase space in the neighborhood of the initial condition using the Mean Exponential Growth factor of Nearby Orbits (MEGNO; Cincotta and Simó, 2000). MEGNO is the so-called fast indicator that makes it possible to distinguish between regular and chaotic motions during an integration of a system over only \( 10^4 \) orbital periods of its outermost planet. This way one can numerically examine a large number of the initial conditions using a reasonable amount of CPU time. As it turns out, the
nominal positions (with respect to the "best-fit" initial condition) of the planets A, B and C are located far from any strong instabilities of the motion in the semi-major axis space. It follows from the full MEGNO analysis that this is also true for the remaining orbital elements which indicates that the system is indeed stable on the Gyr timescale.

3. A Jovian Planet Around PSR B1620-26

The second pulsar orbited by a planet-mass body is a neutron star-white dwarf binary PSR B1620-26 in the globular cluster M4 (Sigurdsson et al., 2003). In this case, the pulsar has a third, substellar-mass companion on a wide, moderately eccentric orbit. The object has been detected, because its dynamical influence on the pulsar induces accelerations that are measurable in the form of higher-order derivatives of its spin period (Backer et al., 1993; Thorsett et al., 1993). The timing analysis of PSR B1620-26 is discussed in detail by Thorsett et al. (1999) and the most recent timing residuals for the pulsar are shown in Figure 3.

A planetary mass of the outer companion to PSR B1620-26 has been recently confirmed by Sigurdsson et al. (2003), who have succeeded in detecting the pulsar’s inner, white dwarf companion with the Hubble Space Telescope. A low mass ($0.34 \pm 0.04 M_\odot$) and a relatively young age ($4.8 \times 10^8 \pm 1.4 \times 10^8$ years) of the white dwarf confirms a prediction implied by the formation scenario for the PSR B1620-26 system proposed by Sigurdsson (1993). In this scenario, the planet orbiting a main-sequence star in the cluster core survives an exchange interaction with a neutron star binary, in which the original white dwarf companion to the neutron star is replaced by the planet’s parent star. Details of a subsequent evolution of the resulting hierarchical triple (Sigurdsson et al., 2003) lead to a prediction that the pulsar’s inner companion should be an undermassive, young and relatively bright white dwarf, which is precisely the case.

Given the mass of the pulsar’s white dwarf companion one can estimate the orbital inclination of the inner binary ($55^{+14}_{-8}$ degrees). This constrains the semi-major axis and the mass of the outer companion to be 23 AU and $2.5 \pm 1 M_{\text{Jupiter}}$, respectively (Sigurdsson et al., 2003). As this mass is obviously in the giant planet range, the PSR B1620-26 planet is not only the oldest one detected so far, but it also represents the only known case of a planet born in a metal-poor environment.

4. Dusty Disks Around Pulsars?

The existence of planet-mass bodies around PSR B1257+12 raises an interesting possibility that at least some pulsars may, like normal stars, be accompanied by protoplanetary or debris disks. All theories of planet formation around neutron stars assume a creation of some sort of a protoplanetary disk out of the material supplied by the pulsar’s binary companion or, possibly, from the fallback of supernova
Figure 2. Time variations of (a) the semi-major axes, (b) the orbital inclinations, and (c) the eccentricities of the orbits of the PSR B1257+12 planets over the first 500,000 yr. Panel (d) illustrates the secular apsidal resonance between the planets B and C parametrized by the critical argument $\theta = \sigma_B - \sigma_C$. $\sigma = \omega + \Omega$ is the longitude of periastron; $\Omega$ and $\omega$ are the longitude of ascending node and the argument of periastron of the planet, respectively (courtesy of K. Goździewski).
Figure 3. Results of the pulse timing analysis for PSR B1620-26. (Upper panel) Residuals after a fit for the spin period, its derivative, standard astrometric parameters, and the inner binary orbit. (Lower panel) Residuals after including a fit for five period derivatives to model the outer, planetary orbit (courtesy of A. Lyne, I. Stairs, and S. Thorsett).

...ejecta (e.g. Podsiadlowski, Phinney and Hansen, 1993, 1993). Of course, properties and composition of such disks may be significantly different from those of the commonly observed disks around T Tauri stars. In addition, the pulsar emission irradiating these hypothetical disks mostly consists of a wind of ultrarelativistic particles. Although the total spindown luminosities of pulsars are, in principle, more than sufficient to heat the dust grains, the efficiency of this process depends on a number of factors that are difficult to predict in absence of sufficient observational constraints (Miller and Hamilton, 2001).

To set the basic constraints on the circumpulsar disk observability with a minimum set of assumptions, one can apply the approach of Foster and Fischer (1996) by assuming that a fraction $f$ of the pulsar spindown luminosity $L$ heats $N$ dust grains of size $a$ to a temperature $T$, and calculate the expected infrared flux as a function of disk parameters and pulsar distance from $fL \sim 4\pi a^2 N \sigma T^4$. These estimates can be compared with the upper flux limits derived from the previous attempts to detect the hypothetical circumpulsar disks with both the space- and the ground-based telescopes at wavelengths ranging from 10 $\mu$m to 3 mm (van Buren and Terebey, 1993 (IRAF); Zuckerman, 1993 (IRTF); Phillips and Chandler, 1994 (JCMT, OVRO); Foster and Fischer, 1996 (IRTF); Graeves and Holland,
Figure 4. Observational limits and theoretical models for the emission from a hypothetical dusty disk in the PSR B1257+12 planetary system. Symbols mark the flux limits set by observations, and the solid curves denote examples of theoretical models, as explained in the text. Dashed lines correspond to the Spitzer Space Telescope $3\sigma$ sensitivity limits calculated for the IRAC and the MIPS detectors (http://sirtf.caltech.edu/SSC).

As an example of typical sensitivities achieved in the previous observations, we summarize the upper flux limits obtained for PSR B1257+12 in Fig. 4. For comparison, we also include theoretical curves for a $T = 20$ K, $300 M_\oplus$ disk consisting of 1 $\mu$m grains, and a $T = 500$ K, $10^{-5} M_\oplus$ ($\sim$1/10 solar system asteroid mass) disk with a 0.1 $\mu$m grain size, for the PSR B1257+12 spindown luminosity $L = 2 \times 10^{34}$ erg s$^{-1}$ and distance $d = 0.62$ kpc. Neither of the two models violates the constraints set by observations, but, of course, one could achieve the same result with other physically plausible realizations of a circumpulsar disk.

5. Discussion

The existence of planets around the millisecond pulsars PSR B1257+12 and PSR 1620-26 has important consequences for astronomy of extrasolar planets. A near 3:2 MMR between the orbits of planets B and C in the PSR B1257+12 system
and the fact that they are nearly coplanar imply that this pulsar’s planetary system has been created as the result of a disk evolution similar to that invoked to describe planet formation around normal stars (Boss, 2003). Together with the true mass measurements of the planets and the long-term system stability calculations described in Section 2, these results offer a fairly complete dynamical characterization of the only known extrasolar planetary system containing terrestrial-mass planets. Its existence provides a demonstration that protoplanetary disks beyond the Sun can evolve Earth-mass planets to a dynamical configuration that is similar to that of the planets in the inner solar system.

The Jupiter-mass planet detected around PSR B1620-26, in an extremely metal-poor environment of the globular cluster M4, represents an outstanding exception to the growing evidence for a positive correlation between the occurrence of planets and the metallicity of their parent stars (Santos et al., 2001; Santos et al., 2003; Fischer et al., 2003). Of course, more such detections would be needed to fully understand the implications of this discrepancy. In particular, is must be remembered that no planets have been detected in a transit survey of the cluster 47 Tucanae, which is a factor 5 more metallic than the M4 cluster (Gilliland et al., 2000). One interesting possibility raised by Sigurdsson et al. (2003) is that an enhanced metallicity of protoplanetary disks could encourage planet migration, which would explain the lack of short period planets in 47 Tuc. Nevertheless, the PSR B1620-26 planet provides a strong observational suggestion that the currently postulated evidence for a dependence of the frequency of planets on the metal content of their parent systems may include biases that are not yet understood.

The early theories of the PSR B1257+12-type planet formation have been summarized by Podsiadlowski (1993) and further discussed by Phinney and Hansen (1993). More recently, Miller and Hamilton (2001) and Hansen (2002) have examined the conditions of survival and evolution of pulsar protoplanetary disks. They have concluded that an initially sufficiently massive (> \(10^{28}\) g) disk would be able to resist evaporation by the pulsar accretion flux and create planets on a typical, \(\sim 10^7\)-year timescale. A quick formation of a massive disk around the pulsar could, for instance, be accomplished by tidal disruption of a stellar companion (Stevens et al., 1992; Phinney and Hansen, 1993) or, possibly, in the process of a white dwarf merger (Podsiadlowski et al., 1991; Livio et al., 1992). Both these processes, although entirely feasible, cannot be very common. In fact, with the exception of PSR B1257+12, no planetary companions have emerged from the precision timing of the known galactic millisecond pulsars (Lorimer, 2001), implying their rarity, independently of the specific formation mechanism.

In the case of the PSR B1620-26 planet, its origin described by Sigurdsson et al. (2003) is dynamically entirely different from the scenarios envisioned for the PSR B1257+12 system. According to Sigurdsson et al., this Jupiter-sized planet has originally formed around a main-sequence progenitor in the core of the M4 cluster and, after an exchange interaction with a neutron star- white dwarf binary, it has been ejected from the core, assuming a wide, eccentric orbit around a newly
formed inner binary, now including the planet’s parent star. Obviously, as such interactions must be quite infrequent, even in the clusters with very dense cores (Sigurdsson, 1993), it will be very difficult to find additional examples of planets around globular cluster pulsars. In any case, it will be worthwhile to continue the precision timing programs of pulsars in globular clusters and search for possible planet signatures in the timing residuals. Similarly, it is possible that the statistics of planets around the field millisecond pulsars will eventually improve as the result of continuing pulsar surveys and the followup timing observations.

As shown in Fig. 4 and discussed, for example, by Graeves and Holland (2000) and Koch-Miramond et al. (2002), the existing IR flux limits for PSR B1257+12 (and a few other pulsars) do rule out massive, $\sim 0.01M_\oplus$ disks similar to those thought to give rise to planets around normal stars (Boss, 2003). However, these limits do not contradict a possibility that some pulsars may be accompanied by much less massive disks with masses ranging from a fraction of the asteroid belt mass to a few hundred $M_\oplus$ over a wide range of temperatures and grain sizes. This conclusion is consistent with the masses of the PSR B1257+12 planets and their disk origin deduced by Konacki and Wolszczan (2003) from timing observations of the pulsar, and with the theoretical constraints on neutron star planet formation scenarios discussed above.

In the absence of new detections of planets around millisecond pulsars further searches for dust around these objects, covering the physically plausible parameter space at a possibly high sensitivity level, is the logical way to meaningfully constrain the models of a creation and evolution of pulsar protoplanetary disks. As shown in Fig. 4, the Spitzer Space Telescope, with its factor of $10^2$–$10^3$ improvement in sensitivity, compared to the instruments previously used to search for dust emission from around pulsars, is an obvious choice for further exploration of the physics of neutron star planetary systems.

**Acknowledgements**

This work was supported by the NASA grant NAG5-13620 and the NSF grant PHY99-07949. The author wishes to thank Drs A. Lyne, I. Stairs and S. Thorsett for permission to display their unpublished timing data on PSR B1620-26 in Figure 3, and Drs K. Goździewski and M. Konacki for their contribution to the results presented in this paper. Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under contract with the National Science Foundation.

**References**


