On The Existence of Planets Around the Pulsar PSR B0329+54

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Results of timing measurements of the pulsar PSR B0329+54 obtained in 1968–2012 using the Big Scanning Antenna of the Pushchino Radio Astronomy Observatory (at 102 and 111 MHz), the DSS 13 and DSS 14 telescopes of the Jet Propulsion Laboratory (2388 MHz), and the 64 m telescope of the Kalyazin Radio Astronomy Observatory (610 MHz) are presented. The astrometric and rotational parameters of the pulsar are derived at a new epoch. Periodic variations in the barycentric timing residuals have been found, which can be explained by the presence of a planet orbiting the pulsar, with an orbital period $P_1 = 27.8$ yr, mass $m_c \sin i = 2M_\oplus$, and orbital semi-major axis $a = 10.26$ AU. The results of this study do not confirm existence of a proposed second planet with orbital period $P_2 = 3$ yr.

1. INTRODUCTION

The pulsar B0329+54 was discovered in 1968 by Cole and Pilkington [1]. In 1979, Demiański and Prószyński [2] suggested that the pulsar may have a planet with a period of three years. In 1985, Cordes and Downs [3] did not confirm this periodicity, while Bailes et al. [4] again found this periodicity in data obtained with the 76 m radio telescope of the Jodrell Bank Observatory.

In 1995, based on newly analyzed data from the Jet Propulsion Laboratory (JPL) [3] and her own data obtained with the Big Scanning Antenna (BSA) of the Pushchino Radio

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Astronomy Observatory (PRAO), Shabanova [5] concluded that the timing data does contain a three-year periodicity, and that variations with a period of about 17 yrs are also present.

In 1999, Konacki et al. [6] again turned to the question of planets. Based on observations with the 100-m Effelsberg radio telescope (Germany) and the 32-m Toruń radio telescope (Poland), they concluded that the new timing data are not described well by the earlier model with two planets, implying that there are no planets around the pulsar.

Hobbs et al. [7] present a timing-residual plot that shows the presence of quasi-harmonic variations covering two periods of a possible planetary companion. However, it was concluded that the variations are most likely due to the timing noise of the pulsar itself. Note that Shabanova et al. [8] agree with the conclusions of Hobbs et al. [7] regarding the absence of planets near this pulsar.

As can be seen from the above references, the question of the existence of planets orbiting PSR B0329+54 remains open. We therefore decided to perform a detailed study based on all currently available data (the pulsar has been observed since 1968).

2. OBSERVATIONS

We used data obtained during 1968–2012, at three radio observatories and at three different frequencies:

1. 1968–1985 – the DSS-13 (26-m diameter) and DSS 14 (64-m diameter) radio telescope of the JPL, operating at 2388 MHz. The observing bands were 12 and 32 MHz [9], and the time spanned by the observations was MJD = 40 105–45 385.

2. 1978–2012 – the PRAO BSA, operating at 102 and 111 MHz. The observing band was 2.5 MHz [8], and the time spanned by the observations was MJD = 43 702–55 973.

3. 1997–2001 – the 64-m radio telescope of the Kalyazin Radio Astronomy Observatory (KRAO) operating at 610 MHz. The observing band was $2 \times 3.2$ MHz [10], and the time spanned by the observations was MJD = 50 645–52 264.

In all, the observations we used for timing of PSR B0329+54 cover 44 yrs, and are still ongoing.

From the start of observations with the LPA, its operating range had been 101–104 MHz, but it was readjusted in 1998 to observe at 109–113 MHz. Therefore, PSR B0329+54 was
observed with this instrument at 102 MHz during 1978–1998, and at 111 MHz from 1998 to the present. A 64-channel radiometer was used for these observations. The channel bandwidth was 20 kHz; a 512-channel spectrum analyzer was used starting in 2005 [11].

Observations of PSR B0329+54 at JPL were made at 2388 MHz, starting in 1968 with the 26-meter DSS-13 antenna with a bandwidth of 12 MHz, and later with the 64-meter DSS-14 antenna with a bandwidth of 32 MHz [9].

Pulsar observations at the KRAO were made using the fully steerable 64-m radio telescope at an operating frequency of 610 MHz [10].

All the recording systems applied pulse accumulation synchronous with the apparent period. In each case, the number of combined pulses was chosen individually, depending on the sampling interval and the width of the frequency channel, in order to guarantee a high signal-to-noise ratio. The accumulation interval for the BSA was determined by the time for the passage of the pulsar through the antenna beam.

In all, 543 pulse arrival times (PATs) were obtained at JPL, 229 at the KRAO, and 3037 at the PRAO.

3. DATA REDUCTION

All the timing data were processed using the Tempo software package. The model for the phase analysis of the PATs included the rotational (the frequency and its derivatives) and astrometric (the coordinates and proper motion) parameters of the pulsar. The delay model is described in detail by Doroshenko and Kopeikin [12], as well as Hobbs et al. [13, 14]. The analysis of the behavior of the residuals in the presence of errors in the parameters determined is also described in these same papers. When processing the entire dataset for the three observatories, it was found [15] that the coordinates of the pulsar cannot be determined simultaneously at different frequencies. Therefore, the position of the pulsar on the sky was first determined separately for the three datasets, after which the timing residuals were reduced to a single plot with common spin parameters.

To minimize the influence of the errors in the pulsar proper motion, its coordinates were reduced to epoch MJD = 48 000, which is close to the middle of the entire time interval.

1 http://tempo.sourceforge.net/
spanned by the observations. Table 1 presents the astrometric and spin parameters of the pulsar.

The analysis performed using the Tempo software yielded timing residuals for PSR B0329+54 after fitting with a cubic polynomial covering the entire time span of the observations. The result is plotted in Figure 1.

As can be seen, the timing residuals indicate the presence of a quasi-harmonic modulation, which suggests the existence of a planet orbiting the pulsar. The plot also shows that the data form a double “noise corridor”, due to the fact that PSR B0329+54 is a mode-switching pulsar. When the mode switches, the shape of the pulse changes and it is simultaneously delayed by approximately 1 ms [16]. We did not take this into account in our present study, and have not analyzed it separately.

We fitted a harmonic curve describing the effect of a possible planet to the residuals, shown in Fig. 2 by the solid curve. The period of the harmonic variations is 28 yrs. After excluding the 28-yr periodicity and variations in the rotation of the pulsar itself, the other, so-called three-year, periodicity first noted by Demiański and Prószyński [2] and then confirmed by Shabanova [5] becomes clearly visible (see Fig. 3). Figure 3 clearly shows that, at the beginning of the observations, in 1968–1978, the variations had the period of 3 yrs and an amplitude of 1 ms, while the character of these variations has changed significantly since the 1990s: the amplitude increased to 1.6 ms and the period increased to 4.4 yr. Such a change in the variations of the residuals is extremely difficult to explain using a model with a planet; this would require the transition of the planet into another, longer-period, orbit under the action of some external force.

4. RESULTS

The question of the existence of a planet is complicated by the fact that a number of pulsars display peculiarities in their rotation, which, under certain conditions, can produce quasi-periodic variations of the PATs, resembling the influence of an external body orbiting the pulsar. The opposite situation is also possible: strictly harmonic deviations of PATs due to a planet can be completely distorted by random variations of the pulsar spin phase, leading to the incorrect conclusion that there is no companion in orbit around the pulsar. Therefore, strictly speaking, the time span of the observations, which covers only two to
three orbital periods, is not sufficient to enable unambiguous conclusions about the presence or absence of a planet around the pulsar. Confirmation of the existence of a planet would require longer series of observations.

Observational studies of binary systems give the semi-major axis of the pulsar orbit projected onto the line of sight and the orbital period, listed in Table 2. These quantities enable calculation of the mass function,

\[ f(m_p) = \frac{(m_c \sin i)^3}{m_p + m_c} = \frac{4\pi^2 (a_p \sin i)^3}{G P_b^2} \simeq 1.04 \cdot 10^{-16} M_\odot. \]  

(1)

If we suppose the pulsar mass to be \( m_p = 1.44 M_\odot \), the mass of the planet is two Earth masses: \( m_c \sin i \simeq 2 M_\oplus \). The semi-major axis of the relative orbit derived from Kepler's third law is

\[ a = \sqrt[3]{m_p P_b^2} \simeq 10 \text{ AU}. \]  

(2)

The calculated parameters of the planet are presented in Table 2.

We cannot currently confirm the existence of a second planet around PSR B0329+54, with an orbital period much shorter than the period of the first planet. The presence of short-period variations with the period 3–4.4 yrs is described well by a sawtoothlike curve, whose nature indicates the action of a mechanism inside or near the pulsar that leads to discontinuous variations of the pulsar’s rate of rotation, with the character of these processes changing after about 20 yrs of timing measurements. This, in turn, could be due, for instance, to different rates of braking of the pulsar due to changes in the energy-loss rate or the periodic reorganization of the internal structure of the neutron star. Firmer conclusions about the origin of the variations in the pulsar’s rotation rate will become possible only after detailed studies of the evolution of the pulse shape, which is the subject of a dedicated future study.

However, the possible existence of a second planet should not be completely lost from sight. Continued observations of PSR B0329+54 are necessary, and additional data may make it possible to finally determine whether this neutron star has a second planet, or what processes give rise to the appearance of quasi-periodicity in the currently observed post-fit residuals. In addition, the amount of observational data currently available is not sufficient to fully cover at least two orbital periods of the first, long-period planet.
5. DISCUSSION

Several groups of researchers are currently observing hundreds of pulsars, but “pulsar” planets remain a fairly rare phenomenon against the background of the thousands of planets discovered around stars in other stages of their evolution. This raises the question of the origin of pulsar planets, in particular, of the planet orbiting PSR B0329+54.

At the moment, there are two models for the origin of pulsar planets.

1. The planet orbiting the neutron star formed after the supernova explosion, from stellar matter that remained in orbit.

2. The planet formed before the pulsar, survived the supernova explosion, and remained in orbit around the pulsar.

Each of these theories has its own properties and conditions.

If the planet forms after the supernova, there must remain after the explosion, formation of the neutron star, and ejection of the stellar envelope enough matter for the formation of this new body, or even of a planetary system, as in the case of PSR B1257+12 [17]. Further, this condition must be met in the presence of the huge expansion velocity of the ejected shell \((10^3 - 10^4 \text{ km/s})\) in the case of a symmetric explosion, or in the case of the motion of the neutron star through the expanding supernova shell, if the explosion was asymmetric.

In the second model, the planet ends up during the supernova explosion in the path of an ejected shell with a mass of several solar masses propagating with a velocity of \(10^3 - 10^4\) km/s. The destruction of the planetary system is mainly brought about by the pressure of the ejected stellar matter, which can exceed the gravitational attraction between the planets and the central star and push the planet or planets out of the stellar system; all this is accompanied by a significant decrease of the mass of the central body. In addition, even if the planet remains in orbit around the star, a solid planet will lose its atmosphere, which will be carried away by the ejected stellar shell, while a gaseous planet will lose some of its mass. Even if the planet survives the supernova explosion, the semi-major axis and eccentricity of its orbit should increase. Thus, the almost perfectly circular orbits of the planets around the pulsar PSR B1257+12 [17] are not consistent with this theory. However, if we take the orbital eccentricity of the planet around PSR B0329+54 with the period \(P_1 = 27.8\) yrs to be
\( \epsilon_1 = 0.236 \), we can assume that the orbit of this planetary companion to the neutron star became elliptical in the process of the supernova explosion.

Answering the question of whether a planet can survive the evolutionary transformation from a regular star to a neutron star, while continuing to orbit this object, requires the construction of a model for the evolution of the planetary orbit during the supernova explosion. This model must take into account all perturbing forces hindering the preservation of the planetary system, and consider models for both symmetric and asymmetric explosions. We plan to explore this in future studies.

6. CONCLUSION

The main results of this study are the following.

1. Timing of the pulsar PSR B0329+54 was carried out in 1968–2012 using observations obtained with the PRAO LPA (102, 111 MHz), the KRAO 64-m radio telescope (610 MHz), and the JPL DSS-13 and DSS-14 telescopes (2388 MHz). We have derived the astrometric and spin parameters of the pulsar at epoch MJD = 48 000.

2. Quasi-periodic variations that are described well by a model with a planet having an orbital period \( P_1 = 27.8 \) yrs were detected in the timing residuals.

3. We have determined the orbital parameters of the inferred planet: its orbital period, orbital eccentricity, semi-major axis projected onto the line of sight, and mass (with accuracy to within the orbital inclination).

4. Despite the presence of short-period variations in the timing residuals, due to the nature of these variations, we were not able to confirm the existence of a second planet orbiting this pulsar with the period \( P_2 = 3 \) yrs.

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Table 1. Astrometric and spin parameters of PSR B0329+54

| Parameters       | Values                                      |
|------------------|---------------------------------------------|
| RAJ              | 03$^h$32$^m$59.373(1)$^s$                  |
| DECJ             | 54$^\circ$34'43.49(2)$''$                  |
| PMRA, mas/yr     | 17                                          |
| PMDEC, mas/yr    | -10                                         |
| $\nu$, s$^{-1}$  | 1.3995410003399(14)                         |
| $\dot{\nu}$, s$^{-2}$ | $-4.011433(2) \times 10^{-15}$            |
| $\ddot{\nu}$, s$^{-3}$ | $3.37(2) \times 10^{-27}$               |
| PEPOCH           | 48000                                       |
| DM, pc/cm$^3$    | 15.4                                        |
| EPHEM            | DE405                                       |

RAJ and DECJ are the right ascension and declination, PMRA and PMDEC the proper motion in right ascension and declination, PEPOCH the epoch to which the coordinates and spin frequency of the pulsar are reduced, DM the dispersion measure, and EPHEM the ephemerides used to reduce the PATs to the barycenter. The numbers in parantheses are the uncertainties in the last significant digits.

Table 2. Parameters of the planet orbiting PSR B0329+54

| Parameters                        | Values       |
|-----------------------------------|--------------|
| Projected semi-major axis, $a_p \sin i$ (ms) | 21.58 ± 0.14 |
| Semi-major axis of relative orbit, $a$ (AU)    | 10.26 ± 0.07 |
| Period, $P_1$ (yr)                 | 27.76 ± 0.03 |
| Eccentricity, $e_1$                | 0.236 ± 0.011|
| Mass of the planet, $m_c \sin i$ ($M_\odot$) | 1.97 ± 0.19  |
Figure 1. Timing residuals of PSR B0329+54 in 1968–2012. The gray curve shows the residuals corresponding to the PRAO data (102 and 111 MHz) and the black curve the residuals according to the JPL data (2388 MHz, on the left) and KRAO data (610 MHz, on the right).
Figure 2. Timing residuals (points) remaining after subtraction of variations of the pulsar spin and a theoretical curve (solid) describing the motion of the first planet.
Figure 3. Shape of the timing residuals after subtraction of the model for the motion of the first planet and the intrinsic variations of the pulsar spin.