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The Pulsar Triple System PSR B1620−26: A Status Report

Abstract

The pulsar PSR B1620−26, in the globular cluster M4, has a low-mass stellar companion and a large frequency second derivative that has been ascribed to acceleration of the binary system in the gravitational field of a second companion object. Recently, we have reported the detection of a decrease in the projected size of the semimajor axis of the binary, which we believe is caused by precession of the binary in the tidal field of the second companion. The implied mass of the second companion is only $\sim 0.01\ M_{\odot}$. In this work, we summarize recent observations of B1620−26, as well as results from modeling the time evolution of the apparent pulsar spin frequency and orbital elements in a hierarchical triple system.

I Introduction

The millisecond radio pulsar PSR B1620−26, in the globular cluster M4, has a binary companion, probably a $\sim 0.3\ M_{\odot}$ white dwarf, in a 191 day, low-eccentricity orbit (Lyne et al. 1988). Unlike other known millisecond pulsars, it has a very large frequency second derivative $\ddot{f}$, implying that the spin-down rate varies on a timescale of ~ 10 yrs (Backer 1993). Neither intrinsic rotational instabilities nor acceleration in the gravitational field of the cluster is likely to produce such a large $\ddot{f}$; the most attractive explanation appears to be a second companion, of either stellar or planetary mass, in a bound, hierarchical orbit around the neutron-star–white-dwarf binary (Backer 1993; Thorsett, Arzoumanian & Taylor 1993; Backer & Thorsett 1995).

The best test of the triple system hypothesis would be a predictive Keplerian fit to data spanning more than one orbit of the outer body. However, because the inferred orbital period is of order a century or more, such a demonstration is beyond our ability: at best, we can observe only a small portion of an orbit, essentially measuring successively higher-order derivatives of the acceleration at a single point.

Of course, even in a hierarchical triple the orbits are not truly Keplerian, because of gravitational interactions between the inner and outer companions. Another test of the triple system hypothesis is therefore to seek perturbations induced on the inner orbit

Table 1: Timing parameters of PSR B1620−26.

Right ascension (J2000.0)	$16^{h}23^{m}38\overset{s}{.}2212(3)$
Declination (J2000.0)	$-26^\circ 31' 53\overset{''}{.}79(2)$
Proper motion RA (mas yr^{-1})	−11.6 (assumed)
Proper motion Dec (mas yr^{-1})	−15.7 (assumed)
Dispersion measure (pc cm^{-3})	62.8626(6)
Spin period P (ms)	11.075750914220(4)
Spin frequency f (Hz)	90.2873320053(3)
$\dot{f}$ (s^{-2})	$-5.4703(7)\times 10^{-15}$
$\ddot{f}$ (s^{-3})	$1.930(3)\times 10^{-23}$
$\dddot{f}$ (s^{-4})	$6.7(6)\times 10^{-33}$
$\ddddot{f}$ (s^{-5})	$-2.1(3)\times 10^{-40}$
Epoch of f (MJD)	48725.0
Projected semi-major axis $x = a_1 \sin i$ (s)	64.809459(6)
Orbital period P_b (s)	16540653(5)
Eccentricity e	0.0253154(2)
Time of periastron T_0 (MJD)	48728.2625(2)
Angle of periastron ω	117.1292(4)
Mass function ($M_\odot$)	7.975×10^{-3}
Advance of periastron $\dot{\omega}$ ($^\circ yr^{-1}$)	$(-2.8\pm 2.0)\times 10^{-4}$
$\dot{P}_b$	$(1.4\pm 1.9)\times 10^{-9}$
$\dot{e}$ (s^{-1})	$3(3)\times 10^{-15}$
$\dot{x}$	$-6.6(0.8)\times 10^{-13}$

NOTE — Position is relative to the JPL DE202 solar system ephemeris. Numbers in parentheses are uncertainties in the final digits quoted. Proper motion is from Cudworth & Hansen 1993. Formal uncertainties are relative to model fit with above parameters. Covariances with unfit parameters (e.g., the fifth frequency derivative) may increase true uncertainties, particularly of $\dddot{f}$ and $\ddddot{f}$.

by the more distant third body. For example, the gravitational tidal force of the outer body on the inner orbit will cause the inner orbit to precess around the normal to the outer orbit. This effect is well known in the solar system, where it is called planetary precession; it may be made manifest through the changing projected size of the inner orbit.

II Observations

We report on observations made at Green Bank and the Very Large Array between March 1988 & August 1996. Details of the observing systems and techniques may be found elsewhere (e.g., Thorsett, Arzoumanian & Taylor 1993).

A timing model was fit to the data using standard techniques. The resulting parameters are given in Table 1.

III Discussion

The early suggestion that the anomalously large second frequency derivative was evidence of a varying gravitational acceleration of the B1620−26 binary has proven robust. The apparent frequency derivative of the pulsar has changed by a factor of three since its discovery; at this pace, the pulsar will appear to begin spinning up in April 2001. Such large fractional variations strongly argue against a model dependent on intrinsic timing noise (Figure 1). Similarly, the timescale of the variation rules out the mean field contribution of the cluster or galaxy, and the probability of a near enough (unbound) close encounter by another cluster star is low (Thorsett, Arzoumanian & Taylor 1993).

Further evidence for the triple hypothesis comes from the very significant measurement of a variation in the projected semimajor axis of the orbit, with timescale $x/\dot{x} \sim 3\,\mathrm{Myr}$. No corresponding variation in P_b is seen, suggesting that $\dot{x}$ is due to a change in the inclination angle i. The simplest understanding of this observation is that the plane of the inner orbit is precessing in the tidal gravitational field of another, noncoplanar, object.

If PSR B1620−26 is a member of a hierarchical triple, then the four measured frequency derivatives provide information about the curvature of a nearly Keplerian orbit. Recently, Joshi & Rasio (1997) have demonstrated how the measurements can be inverted to solve Kepler's equation, with a single free parameter (such as the eccentricity of the outer orbit). Such timing measurements only probe the projection of the motion on the line of sight, so a number of angles (the inclinations and relative orientation of the orbits) remain unresolved. Orbital perturbations, however, depend upon these angles as well. Using Monte Carlo techniques, Joshi and Rasio have used the spin frequency derivatives, the measured $\dot{x}$, and limits on changes in the other orbital elements to conclude that the most likely second companion has a mass of only $0.01 \pm 0.005\ \mathrm{M}_{\odot}$, and an orbital radius of $\sim 40\,\mathrm{AU}$.

The birth and survival of such a system pose substantial theoretical challenges (Sigurdsson 1995; Joshi & Rasio 1997). Ionization of the "planet" or brown dwarf will occur by close encounters between the triple and other cluster stars in a timescale of $\sim 2 \times 10^7$ yr (Joshi & Rasio 1997). The planet may have been formed around

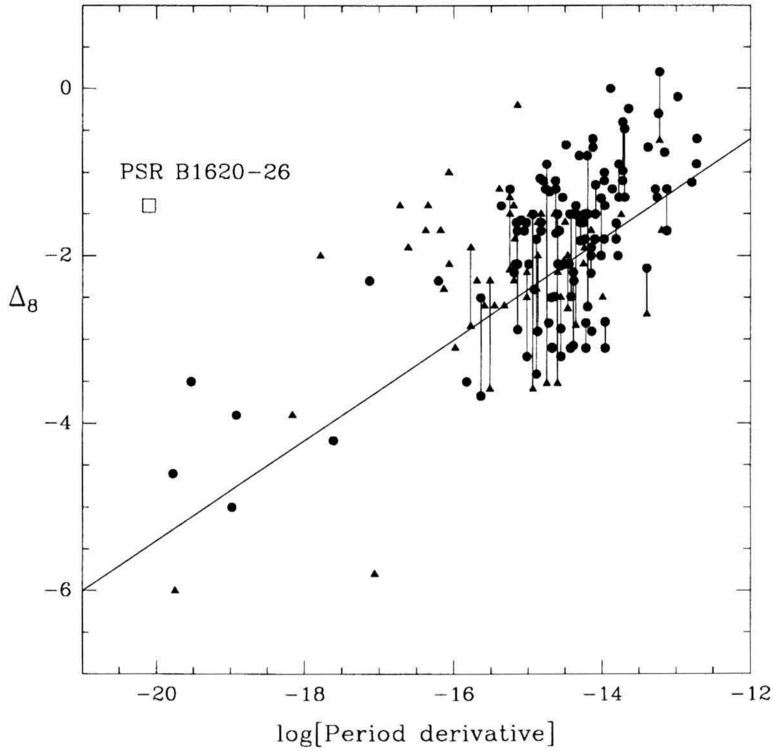

Figure 1. PSR B1620−26 $\ddot{f}$ relative to intrinsic timing noise observed in a sample of pulsars (after Arzoumanian et al. 1994). The parameter $\Delta_8 \propto \log|\ddot{P}|$ is a measure of residual timing noise after subtraction of a quadratic phase model. Triangles are upper limits, and the open box is the location of B1620−26, assuming a typical millisecond pulsar magnetic field of 3×10^8 G.

another star, and exchanged recently into the preexisting pulsar binary during a close encounter, but because the likelihood of the planet remaining bound after the encounter is small, the implied number of such planets orbiting stars in globular clusters must be correspondingly large.

Because such a system is so unexpected, it is very important to continue to improve the observations. Measurement of higher order frequency derivatives, as well as time variations of ω and e, will further constrain the nature of the outer companion, and measurement of an orbital period derivative will test the basic acceleration picture, since we expect $\dot{P}_b/P_b = \dot{P}/P$.

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