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PSR B1620−26: A BINARY RADIO PULSAR WITH A PLANETARY COMPANION?

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ABSTRACT

PSR B1620−26, in the globular cluster M4, is a millisecond pulsar with a ∼0.3 $M_\odot$ companion in a ∼0.7 AU orbit. It was recently realized (Backer 1993) that timing observations of this pulsar show, in addition to a linear spin-down, a large-period second derivative naturally interpreted as evidence for a varying acceleration, or jerk, of the pulsar binary. We describe timing observations of PSR B1620−26 taken over a 5 year period. The measured acceleration and jerk are inconsistent with acceleration by the mean gravitational field of M4, and an encounter with another star close enough to cause the observed acceleration is very unlikely. The data are consistent with acceleration by either a planet in a ∼10 AU orbit or a star in a ∼50 AU orbit. We therefore believe that PSR B1620−26 is likely to be either the first pulsar in a triple stellar system or part of the first binary star system with a planet, possibilities that can be distinguished with further observations over the next decade or two.

Subject headings: binaries: general — globular clusters: individual (M4) — planetary systems — pulsars: individual (PSR B1620−26)

1. INTRODUCTION AND OBSERVATIONS

Shortly after its discovery, pulsar B1620−26, in M4, was found to have a binary companion, most likely a 0.3 $M_\odot$ white dwarf, in a 191 day, low-eccentricity orbit (Lyne et al. 1988; McKenna & Lyne 1988; Foster 1990). Continued observations, however, showed that the published pulse timing models failed to properly predict the pulsar period and phase at later epochs (Thorsett 1991). Finally, Backer (1993) realized that the timing observations could be explained with the addition of another parameter to the timing model—a nonzero frequency second derivative, $\ddot{f}$—which he suggested might be due to the presence of a planetary companion.

We have observed PSR B1620−26 using the 43 m telescope at Green Bank, West Virginia, and the Very Large Array in New Mexico. At Green Bank, observations were made at 3 month intervals between 1989 August and 1993 January. At each epoch, observations were made in two frequency bands—either 400 or 800 MHz, and 1330 MHz—using the "Spectral Processor" fast-Fourier transform spectrometer to synthesize 512 channels across a 40 MHz passband (256 channels across 20 MHz before 1991 February) in each of two orthogonal polarizations. At the VLA, observations were made every 2 months between 1990 November and 1993 January, using a filterbank and the "High Time Resolution Processor" to divide a 50 MHz bandpass at 1660 MHz into 14 slightly overlapping 4 MHz channels. At both observatories, the signal in each frequency channel was averaged synchronously with the predicted topocentric pulsar period to produce a single integrated pulse profile every 5 minutes. The observing hardware and procedure has been described in detail elsewhere (Thorsett 1991; Stinebring et al. 1992; Nice & Thorsett 1992).

Analysis of the pulse arrival times was carried out with the standard software package Tempo (Taylor & Weisberg 1989). The integrated profiles were cross-correlated with a high signal-to-noise ratio mean profile to measure the offsets between the start of each integration and the arrival of a pulse near the center of the integration. The arrival times were fitted with a model that included the pulsar spin frequency and its first two derivatives, the pulsar position and dispersion measure, and the parameters of the binary system: the orbital period, projected semimajor axis, eccentricity, and angle and time of periastron. The model parameters were varied, and the differences between the model and observed arrival times were minimized in a least-squares sense. In addition to the data described above, the analysis included timing data taken at six epochs between 1988 March and 1989 June with an earlier observing system at Green Bank (Foster 1990). The resulting pulsar parameters are gathered in Table 1, and the daily average postfit timing residuals are displayed in Figure 1.

2. DISCUSSION

Except for its anomalously large frequency second derivative, PSR B1620−26 is a fairly typical millisecond pulsar in a low-mass binary system. It is located 44″ from the center of M4, projected inside the 55″ core radius (Goss, Kulkarni, & Lyne 1988).

The measured mass function of PSR B1620−26 requires a minimum companion mass (assuming a 1.35 $M_\odot$ pulsar) of 0.28 $M_\odot$, or a median companion mass (for a random orbital inclination) of about 0.32 $M_\odot$, though the actual mass may be several times larger if the orbit is highly inclined to the line of sight. This companion is probably the white dwarf remnant of the giant star whose evolution-driven mass transfer spun the pulsar up to millisecond periods. The eccentricity $e = 0.025$ of PSR B1620−26 is several orders of magnitude larger than that of most other low-mass binary pulsars, however, and much too high to remain after orbital circularization occurs during mass transfer; Phinney (1992) has argued that it is consistent with

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TABLE 1

TIMING PARAMETERS OF PSR B1620−26

Parameter	Value
Right ascension (J2000.0)	$16^{h}23^{m}38^{s}.2228(6)$
Declination (J2000.0)	$-26°31'53''.71(7)$
Dispersion measure (cm^{-3} pc)	62.8637(20)
Spin period P (ms)	11.075750876440(11)
Spin frequency f (Hz)	90.28733231326(9)
$\dot{f}$ (s^{-2})	$-6.443(2) \times 10^{-15}$
$\ddot{f}$ (s^{-3})	$1.873(9) \times 10^{-23}$
$\dddot{f}$ (s^{-4})	$10(11) \times 10^{-33}$
Epoch of f (JD)	2,448,127.5
Projected semimajor axis x (s)	64.809476(13)
Orbital period P_b (s)	16540659.6(2)
Eccentricity e	0.0253147(5)
Time of periastron T_0 (JD)	2,449,111.6483(4)
Angle of periastron ω	117.1296(7)
Mass function ($M_{\odot}$)	7.975×10^{-3}
Advance of periastron $\dot{\omega}$ (degrees yr^{-1})	$(-5 \pm 12) \times 10^{-4}$
$\dot{P}_b$	$(2 \pm 10) \times 10^{-9}$

NOTE.—Position is relative to the JPL DE200 solar system ephemeris. Numbers in parentheses are uncertainties in the final digits quoted.

the perturbation of a once circular orbit during close encounters with other cluster stars.

The large $\ddot{f}$ of PSR B1620−26 is remarkable. It is almost certainly not an intrinsic property of the pulsar: at the current rate of change, $\dot{f}$ will change sign (from spin-down to spin-up) in less than a decade. The second frequency derivative can be written $\ddot{f} = n\dot{f}^2/f$, where n is the braking index; for magnetic dipole spin-down $n = 3$ (Manchester & Taylor 1977), so $\ddot{f}_{md} = 1.5 \times 10^{-30}$ s^{-3}, some seven orders of magnitude smaller than the observed value. It is possible that the observed $\ddot{f}$ is a sign of timing noise, such as is common for young pulsars, but timing noise is expected to be negligible for old millisecond pulsars like PSR B1620−26 (Stinebring et al. 1990; Cordes 1993). It is also possible that we are observing the recovery from a timing "glitch" that occurred just prior to the pulsar's discovery, although glitches have previously been observed only in the youngest pulsars. In a glitch, f increases suddenly, while the magnitude of $\dot{f}$ temporarily increases as f exponentially decays to its preglitch value. In the largest glitches previously observed in other pulsars, $\Delta\dot{f}/\dot{f} \sim 1\%$ and the decay time scale $\tau \lesssim 1.5$ yr, while a putative glitch of PSR B1620−26 would require $\Delta\dot{f}/\dot{f} \gtrsim 50\%$ and $\tau \gtrsim 5$ yr. While we believe that such a glitch in an old pulsar is unlikely, only continued timing observations over the next few years can rule this out.

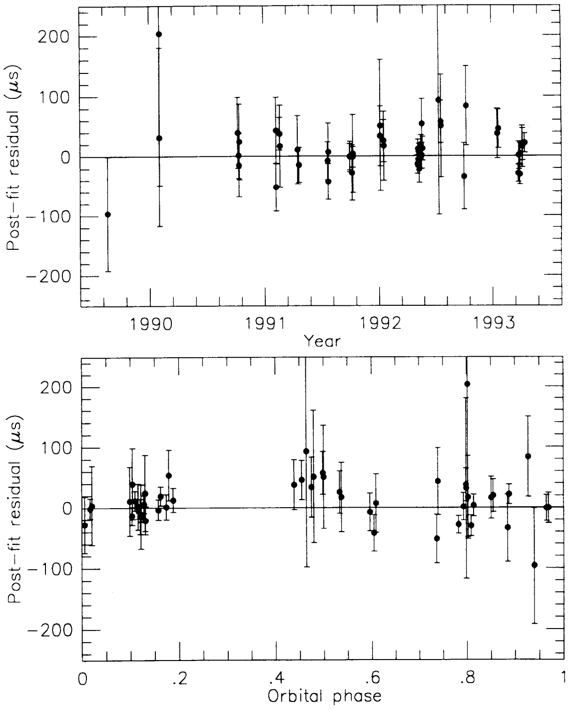

FIG. 1.—Daily averages of the postfit timing residuals plotted as a function of (*upper*) date and (*lower*) orbital phase. The best data have uncertainties of about 12 μs in the daily average pulse arrival times, while the median uncertainty is about 35 μs.

We believe it is most likely that the observed $\ddot{f}$ is caused by a varying gravitational acceleration, or jerk, on the pulsar:

$$\frac{\ddot{f}}{f} \approx \frac{\dot{\boldsymbol{a}} \cdot \boldsymbol{n}}{c} \equiv \frac{\dot{a}_l}{c} \approx 2 \times 10^{-25}\ s^{-2} ,$$

where $\dot{\boldsymbol{a}}$ is the jerk and $\boldsymbol{n}$ is a unit vector in the direction of the pulsar. Gravitational acceleration has been observed in pulsar timing data before: several pulsars in the clusters M15 and Terzan 5 have negative apparent period derivatives (Wolszczan et al. 1989; Anderson 1992; Nice & Thorsett 1992), almost certainly due to acceleration in the mean gravitational field of the cluster, and differential galactic acceleration makes a small but important contribution to the apparent orbital period variation of the binary pulsar PSR B1913+16 (Damour & Taylor 1991).

Of course, a component of acceleration along the line of sight will similarly contribute to the observed frequency first derivative:

$$\frac{\dot{f}}{f} = \frac{\dot{f}_0}{f} + \frac{\boldsymbol{a} \cdot \boldsymbol{n}}{c} \equiv \frac{\dot{f}_0}{f} + \frac{a_l}{c} ,$$

where $\dot{f}_0$ is the frequency derivative measured in the rest frame of the neutron star. Because $\dot{f}_0$ is not known, a_l cannot be determined unambiguously from a measurement of $\dot{f}$. Still, the fact that $\dot{f}$ has already varied by about 40% since the pulsar's discovery requires that $a_l/c \sim \dot{f}/f$. An indirect supporting argument comes from the implied magnetic field strength, $B \propto (-\dot{f}/f^3)^{1/2}$. Unless more than 90% of the measured $\dot{f}$ is due to acceleration, PSR B1620−26 will have a larger implied field than that measured for any other millisecond pulsar except PSR B1802−07, whose magnetic field measurement may itself be biased by acceleration in the core of NGC 6539 (D'Amico et al. 1993). (It must be noted, however, that a large magnetic field cannot be ruled out on theoretical grounds.) We therefore believe it likely that $a_l/c \approx \dot{f}/f = -7 \times 10^{-17}\ s^{-1}$. As an acceleration will contribute similarly to an apparent $\dot{P}_b$, we expect that $\dot{P}_b \approx (-\dot{f}/f)P_b = 1.2 \times 10^{-9}$, which should be measurable in less than a decade of additional observations.

If we believe that the observed spin frequency derivatives are caused by acceleration, then what is the accelerating mass? The cluster itself is one candidate. M4 is a low density cluster, however, with a line-of-sight velocity dispersion of giant stars of only 3.9 ± 0.7 km s^{-1} (Peterson & Latham 1986) and a central mass density of roughly 1–2 × 10^4 $M_{\odot}$ pc^{-3} (Phinney 1993). While the precise values of a_l and $\dot{a}_l$ depend on the unmeasurable line-of-sight component of the distance of PSR B1620−26 from the cluster core, models predict a maximum cluster acceleration of only $|a_{\rm cl}|/c \sim 4 \times 10^{-18}$ s^{-1} and typical cluster jerk $|\dot{a}_{\rm cl}|/c \lesssim 10^{-29}$ s^{-2} (Phinney 1993), much too small to account for the observed acceleration and jerk. Phinney (1993) has also considered acceleration of PSR B1620−26 by a close encounter with another cluster star, but finds that the probability that another star is passing near enough to the pulsar to create the observed jerk is only $\sim 2 \times 10^{-5}$, and even then the motion of the passing star must be very nearly along our line of sight to avoid producing too large an acceleration. On the remote chance that the source of acceleration is a passing star, future timing measurements of $\ddddot{f}$ and higher frequency derivatives will allow the determination of its hyperbolic orbit.

The most likely source of acceleration is a third body in a bound orbit around the pulsar binary system. Unfortunately, only a limited amount of information about the orbit of this body is available from measurements of $\dot{f}$ and $\ddot{f}$ and the measured limits on $\dddot{f}$. The region in orbital parameter "phase space" allowed is quite complex, especially for highly eccentric orbits, and its full exploration is beyond the scope of this *Letter*.

Several authors (Backer 1993; Phinney 1993; Sigurdsson 1993) have suggested a sub-Jovian planet as a likely accelerating body. Considering a circular orbit, they conclude that a planet with mass m_3 between about 14 and 400 $M_\oplus$ is most likely, with an orbital period greater than about 15 yr and a semimajor axis greater than 7 AU. In fact, the new $\dddot{f}$ limit rules out a circular orbit with period less than about 110 yr, if $a_l/c \sim \dot{f}/f$. No such simple limits are derivable for eccentric orbits, but reasonable solutions can be found for $m_3 = 80\ M_\oplus$, $P_b = 10$ yr, and $e > 0.4$, for example.

A number of scenarios have been proposed for the creation of the two planets observed orbiting another millisecond pulsar, PSR B1257+12 (Wolszczan & Frail 1992). For a general review, see papers collected in Phillips, Thorsett, & Kulkarni (1993). Several of these models can be suitably modified to account for a planet orbiting a low-mass binary pulsar. In particular, Tavani & Brookshaw (1992) have suggested that some fraction of the mass lost from the companion during the low-mass X-ray binary stage (during pulsar spin-up) may form a circumbinary disk, out of which planets could condense in less than 10^6 yr. In the case of PSR B1257+12, without a massive companion, the model requires that the donor star was completely destroyed, either during the X-ray binary phase or by an evaporative wind from the radio pulsar, but the presumably more massive companion of PSR B1620−26 has survived. This formation model does not depend on the globular cluster environment; it predicts that planets may also be found orbiting low-mass binaries in the galactic disk.

Sigurdsson (1993) has suggested an alternate model for the formation of a binary millisecond pulsar system with a planetary companion in a globular cluster, beginning with an encounter between a neutron star white dwarf binary and a main-sequence star orbited by a planet in a ~ 1 AU orbit. In numerical simulations, he has demonstrated that in about 10% of exchange encounters in which the main-sequence star replaces the white dwarf, the planet is retained in a stable, moderately eccentric orbit around the new binary with semimajor axis $a \lesssim 30$ AU. If the main-sequence star has a number of planets, the cross section increases proportionately. Because the probability of an exchange encounter is negligible except in dense stellar environments, Sigurdsson's model does not predict planets orbiting low-mass binary pulsars in the disk.

Regardless of the origin of such a planet, its long-term prospects are threatened by close encounters with other cluster stars, which can "ionize" the planet from its circumbinary orbit since its binding energy is much less than the typical kinetic energy of these stars. The timing age of the pulsar is $(-f)/(2\dot{f}) \approx 2 \times 10^8$ yr, but because of the uncertain acceleration contribution to $\dot{f}$ this is likely to be an underestimate, and the true age may be 10^9 yr or more. The ionization time scale for a planet in M4 is much shorter:

$$t_{\rm ion} \sim 5 \times 10^7 \left(\frac{10\ {\rm AU}}{a}\right)\left(\frac{\rho_c}{\langle\rho\rangle}\right) {\rm yr}\ ,$$

where $\langle\rho\rangle$ is the time average density in the system's neighborhood and ρ_c is the density of the core of M4 (Sigurdsson 1992b; Phinney 1993). Thus it is unlikely that a planet formed at the same time as the binary system will have survived to the present day, unless $\rho_c/\langle\rho\rangle \gg 1$. In Sigurdsson's model, the exchange encounter induces a recoil velocity of the binary of $\sim$9–15 km s^{-1}, sending the binary and planet on a wide radial orbit into low-density regions away from the cluster core, where the ionization time scale may be long; the binary sinks back into the core due to dynamical friction in $\sim 10^9$ yr. However, the pulsar is most likely $\sim$1.5 core radii from the cluster center, so $\rho_c/\langle\rho\rangle \gg 1$ only in the unlikely case that the pulsar has only just reentered the core region. In addition, as noted above, Phinney (1992) has suggested that the small eccentricity of the binary orbit is consistent with an origin in perturbations by near encounters with other stars, and these encounters are likely to have stripped the planet from the system. Sigurdsson (1993) has suggested that more distant encounters may have perturbed the eccentricity of the planetary orbit, which in turn perturbed the binary, but detailed calculations have not yet been done.

Ionization can be prevented if the third body is in a hard binary orbit around the other two. This is possible if it is a third massive star, rather than a planetary mass object. Such a system is allowed by the timing observations only if $\omega \sim 0°$ (i.e., the major axis of the orbit is nearly perpendicular to the line of sight). Again, the observations poorly constrain the characteristics of the orbit. For example, if the third body is a 0.8 $M_\odot$ star in a 250 yr, $e = 0.8$, $\omega = 348°$ orbit (so $a = 54$ AU) inclined at 45° to the line of sight, then a current true anomaly of $v = 189°$ (comfortably near apastron, where the object spends most of its time) will produce the observed acceleration and jerk without violating current limits on $\dddot{f}$. Smaller orbits are allowed if the inclination to the plane of the sky is small: for example, $m_3 = 0.8\ M_\odot$, $P_b = 120$ yr, $e = 0.9$, $i = 15°$, $\omega = 354°$, and $v = 183°$ (and $a = 33$ AU). If the third body is another 1.35 $M_\odot$ neutron star, then even harder binaries can be formed.

A hierarchical triple system like the one hypothesized could be primordial, or it could be formed in several different ways. One possibility is in the collision of a binary (say, a neutron star and white dwarf) and a single star (say, a giant). If the velocity of the incoming star is low, there is a significant probability that the three stars will form a resonant, quasi-stable triple system. During the system lifetime of approximately 10–100 typical crossing times, there are numerous potential close encounters between the neutron star and giant, greatly increasing the tidal capture cross section. If enough energy is dissipated in the tidal capture, then the entire triple system can be left stable. The tidally captured star then transfers mass to the neutron star, expanding its orbit to that currently observed in the inner binary.

Binary-binary interactions are probably a more significant source of three-body systems. The binary fraction in globular clusters, though poorly known, is probably 10% or more (Pryor et al. 1989; Hut et al. 1992). With mass segregation, the binary fraction in the cluster core is much higher, so binary-binary collisions are not uncommon. Simulations show that collisions of two hard binaries with similar binding energies produce hierarchical triple systems and a runaway star in ~20% of close collisions, and in up to 50% of collisions involving binaries with disparate semimajor axes, in which one binary acts something like a single point mass (Mikkola 1983, 1984; Hut 1992). Since the excess binding energy is carried away by the runaway star, these triple systems can be stable.

Unless the mass of the second companion is somewhat greater than 1.35 $M_\odot$ (e.g., a black hole or second hard binary), the orbits allowed by the timing data are only moderately hard—near the critical boundary where interactions with cluster stars are more likely to ionize the companion than to harden the orbit. The effect of close encounters on binary orbits has been widely studied (Heggie 1975; Hut & Bahcall 1983; Sigurdsson 1992a). Encounters with other field stars will, on the average, result in only a small energy exchange with the binary, which will slowly perform a random walk in binding energy away from this (unstable) critical point until it either softens to the point it is rapidly ionized or hardens to the point that further interactions are likely only to continue to harden it (Sigurdsson 1992a). The influence of the inner hard binary on the overall stability of the triple system has not been carefully studied. Mikkola (1983) has speculated that the outer orbit may act as an energy pump between the inner binary and the outer field stars.

We are not aware of numerical or analytical evaluations of the time scale for disruption or hardening of a moderately hard binary with component masses somewhat greater than that of typical cluster stars (analytic work has concentrated on asymptotic behavior for very hard or very soft binaries, while numeric work has dealt primarily with the equal mass case). The mean time between encounters for the binaries of interest is $\tau \sim 2 \times 10^8$ yr or less, with a very large uncertainty. Since encounters will result at first in small random steps in binding energy away from the critical value, a system like the one proposed will usually survive several encounters before ionization or significant hardening; nonetheless, it is likely that the expected lifetime of such a system will be somewhat shorter than the cluster and pulsar lifetimes. It is interesting to note that the third star may not be the one the triple was created with, but might be a heavier star (or binary) swapped into the system in an exchange collision. Such an exchange widens the binary while hardening it, with $a_f/a_i \sim m_f/m_i$ since the energy changes only slightly, so an earlier configuration may have had a smaller interaction cross section and a longer lifetime.

Only the continued observation of this very interesting pulsar can confirm the presence of a second companion. If the planetary hypothesis is true, then the orbital parameters of the planetary orbit will be determined in a time $T \lesssim P_b$, probably decades or maybe within the next few years. If the orbit is very eccentric, then the planet will spend only a very short time near periastron, and because accurate orbital determination depends on correct numbering of pulses across the periastron passage, it is critical that this range of orbital phase be well sampled observationally. It is therefore very important that regular, closely spaced timing observations continue, and that the data be quickly processed to monitor for the signs of an approaching periastron passage.

If the PSR B1620−26 binary is orbited by a massive body in a several century orbit, then the complete characterization of the orbit must await a future generation of pulsar astronomers. In principle, however, the orbital elements can be determined with interesting precision by the measurement of higher order frequency derivatives (i.e., line-of-sight projections of higher order velocity derivatives). Much theoretical work also remains to be done, especially an investigation into the formation and long-term stability of planetary systems in globular clusters, and of the interaction between a hierarchical triple system and cluster stars. The confirmation of a planetary companion would strongly reinforce the idea that planets, though hard to find, are not hard to make. The confirmation of a stellar mass companion would focus new attention on the role of many-body systems in the dynamics of the dense cores of globular clusters.

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