Part 2

Timing, General Relativity and Astrometry

Section B. Timing Irregularities

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Periodicities in Rotation and Pulse Shape in PSR B1828−11

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Abstract. We report on the observation of highly-periodic, correlated variations in the rotation and pulse shape of PSR B1828−11. Three harmonically-related periodicities of 100, 500 and 250 days are seen in both the rotation rate and profile shape. The 0.7% modulation in period derivative is apparently related to oscillatory changes in the magnetospheric configuration. The origin of the periodic effects most likely lies in the free precession of the neutron star.

1. Introduction

PSR B1828−11 (PSR J1830−1059) is a young, 405-ms pulsar (Clifton & Lyne 1986) which is observed on about 30 occasions each year at intervals of between one day and about 2 months, using the 76-m Lovell radio telescope at Jodrell Bank; the complete data set spans nearly 13 years. Observations of roughly 30 minutes' duration are conducted at frequencies around 1400 MHz or 1600 MHz.

The pulse profile is unusually narrow, with a width of roughly 3° of pulse phase at half-maximum. We have found that the integrated pulse profile is not stable, causing changes in pulse arrival time of about 1 ms. The pulse consists of a comparatively wide component with a central, narrower peak which varies in intensity on timescales of several months, with predominantly smooth changes punctuated by periods of "dither" between extremes. Individual profiles were found to be described by a linear combination of the two extreme profiles; therefore two standard profiles approximately representing the two extremes (one wide, one narrow) from nearby days were chosen and aligned with the best ephemeris (Fig. 1). An iterative frequency-domain routine was used to determine the relative strengths of the standard profiles required to synthesize the daily profiles. A "shape parameter" is then defined as $S = \frac{A_N}{A_N + A_W}$, where A_N and A_W are the fit heights of the narrower and wider standard profiles respectively, so that $S \approx 1$ for the narrowest pulses and $S \approx 0$ for wider ones.

The pulse times-of-arrival (TOAs) used in the timing analysis are also derived from this shape-fitting procedure; the errors in the TOAs are limited by random noise to about 0.2 millisecond. As the 1600-MHz observations were few in number, the same two standard profiles were used for these data as for the 1400-MHz observations; however the 1600-MHz points were used only in the timing analysis, and not in studying the variations of the pulse profile shape.

Table 1. Measured and Derived Parameters of PSR B1828−11.

Period, P	405.039883158(8) ms
Period Derivative, $\dot{P}$	$60.03243(9) \times 10^{-15}$
Period Second Derivative, $\ddot{P}$	$-1.70(3) \times 10^{-25}$ s^{-1}
Epoch of Period	MJD 48958
Right Ascension, α(J2000)	$18^{\rm h}30^{\rm m}47^{\rm s}.583(7)$
Declination, δ(J2000)	$-10^\circ\ 59'\ 29''.33(12)$
Dispersion Measure, DM	159.7(10) cm^{-3}pc
Magnetic Field, B	5.0×10^{12} G
Characteristic Age, τ_c	0.11 Myr

Table 1 presents the adopted long-term timing solution for PSR B1828−11. The timing residuals Δt relative to this simple model are shown in Fig. 2, covering the 13-year span of our observations. More than four cycles of an evolving double-peaked pattern with period of about 1000 days can be seen. Two cycles of this pattern have been previously reported, with the speculation that they might have a planetary origin (Bailes et al. 1993). It was also thought possible that the pattern was a statistical fluke arising from timing noise; however with the current length of the data set this can clearly no longer be considered a possibility. To study the pattern in detail, we have calculated the observed residuals ΔP in period and $\Delta \dot{P}$ in slowdown rate. Fig. 3 shows these data for the last 2000 days, where the observations are most closely spaced, together with the timing residuals Δt from which they were derived and the mean values of the pulse shape parameter $\langle S \rangle$. The continuous lines for ΔP and $\Delta \dot{P}$ were obtained by fitting three harmonically-related sinusoids to ΔP. There is a nearly perfect correlation between the variations in $\langle S \rangle$ and in $\Delta \dot{P}$, although this is not obvious from the observed timing residuals themselves.

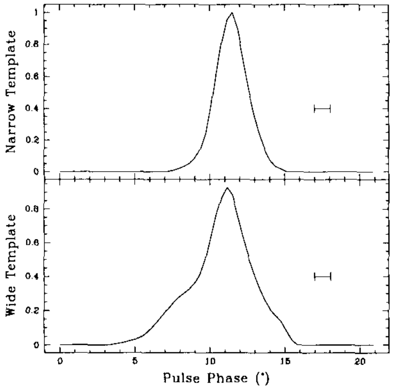

Figure 1. The two "standard profiles" of PSR B1828−11. The horizontal bars represent the instrumental time-resolution.

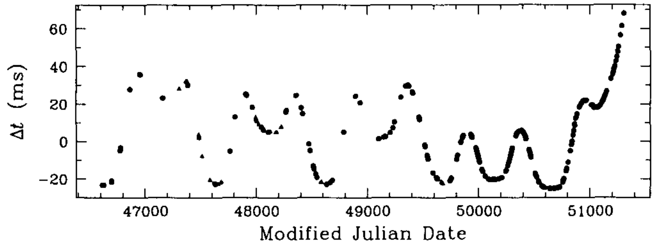

Figure 2. Post-fit timing residuals Δt for PSR B1828−11 after fitting for spin-down parameters.

We performed a Fourier analysis to study the spectral content of the phenomena, using a one-dimensional CLEAN algorithm (e.g. Roberts et al. 1987) for the timing residuals because of the uneven sampling within that data set. The spectra of the residuals in Δt, period ΔP and derivative $\Delta\dot{P}$ as well as $\langle S\rangle$ all exhibit clear harmonically-related periodicities of approximately 1000, 500 and 250 days, and confirming that the variations are related. There is also a strong indication of the presence of a further harmonically-related periodicity of approximately 167 days in both shape and rotation.

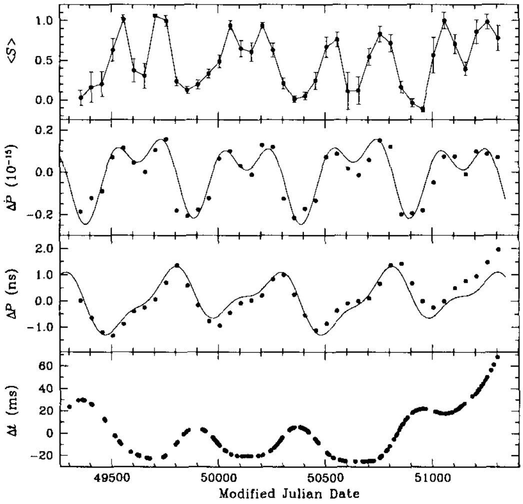

Figure 3. Residuals in arrival time Δt, period ΔP and derivative $\Delta\dot{P}$, relative to the spin-down model given in Table 1, and the mean pulse shape parameter $\langle S\rangle$ for the most recent 2000 days of observations. The solid curves indicate the predictions of a fit of three harmonically-related sinusoids to ΔP.

2. Precession, planets or superfluid oscillation

The close relationship between changes in the beam shape and the spin-down torque acting on the pulsar suggests a common origin within the magnetosphere. The changes in $\dot{P}$ may be due to a change in the inclination angle α between the spin and magnetic axes, which could also change the viewing angle of the radio beam. Within the context of the rotating magnetic dipole model,

$$\dot{P} = \frac{8\pi^2 m^2 \sin^2 \alpha}{3c^3 I P}, \tag{1}$$

where c is the speed of light, I the moment of inertia and m the dipolar magnetic moment of the neutron star. The observed 0.7% variation in $\dot{P}$ therefore implies a fractional change of similar magnitude in $\sin^2 \alpha$, or a variation of 0.3° for $\alpha \sim 60°$ – that is, roughly one-tenth of the observed profile width. High-precision polarization observations at different epochs may allow a fit of α and reveal whether it is actually changing as predicted by this model.

The remaining question is what physical mechanism is causing and setting the timescale for these related variations in S and $\Delta\dot{P}$. We have identified three potential explanations concerned with the interior of the neutron star, planetary bodies and free precession.

While the phenomena of glitches and timing noise have their origins within the interior of the neutron star, their effects are distinctive and seem to be unrelated to the behaviour of this pulsar (Lyne 1996). Conceivably, some form of oscillation within the neutron star interior could be involved. For instance, the periods of Tkachenko oscillations of the neutron superfluid vortex array, which carries much of the angular momentum of the neutron star, depends on the size on the star and the square root of the pulse period (Tkachenko 1966). A quasi-periodicity of between 15 and 30 months has been reported in the Crab pulsar (Lyne et al 1993), but no persistent periodic components which might be attributed to such oscillations have been reported hitherto in any other pulsar. Tkachenko oscillations are expected to result in a 4-month wobble in the Crab pulsar, and a 13-month wobble in PSR B1828−11 (Ruderman 1970, Lamb et al. 1978). While the latter is of similar timescale to the reported periodicities, the theory does not easily explain the existence of multiple harmonics in the PSR B1828−11 timing residuals. Furthermore, no interior clock mechanism provides an obvious explanation for any associated profile-shape changes.

A second possible explanation of the apparent periodicity in the rotation is motion of the neutron star resulting from orbiting planetary bodies (Wolszczan & Frail 1992). Naturally, in this case the apparent changes in period would be due to a changing Doppler effect, and hence would not in fact be caused by the magnetospheric variations. The profile shape changes might then be explained by the magnetic interaction of the planets and the neutron star's magnetosphere, similar to the interaction between the magnetospheres of Io and Jupiter (e.g. Kennell & Coroniti 1979), although in this case the distances are much greater and it would be necessary for at least two of the planets to be involved in the interaction, making this scenario somewhat contrived. Assuming that the pulsar has a mass of 1.35 $M_\odot$ (Thorsett & Chakrabarty 1999), the Keplerian orbital radii identified with the three harmonically related sinusoids are 0.9, 1.4 and 2.2 AU. The corresponding planet masses would then be somewhat larger than that of the Earth: $3.1\,\mathrm{M}_\oplus/\sin i$, $10.2\,\mathrm{M}_\oplus/\sin i$ and $4.6\,\mathrm{M}_\oplus/\sin i$, where i is the orbital inclination angle. Satellites in harmonically-related orbits are known, for instance, in the case of Jupiter and its three largest moons (e.g. Sinclair 1975), and in the case of the planetary system around PSR B1257+12 (Wolszczan & Frail 1992, Rasio et al. 1992, Wolszczan 1994). The orbital frequencies of the Jovian satellites follow the same 1:2:4 harmonic relationship as those of the hypothetical planets of PSR B 1828−11; moreover, their orbital phases fit the relationship $-2\phi_1 + 3\phi_2 - \phi_3 = 180°$ (e.g. Sinclair 1975). Interestingly, the uncertainties in the phases of our three fit sinusoids are sufficiently large that we cannot rule out that these phases may also fit this equation. However, attempts to fit either circular or eccentric planetary orbits directly to the timing data leave large systematic trends in the residuals, although additional timing noise, larger planets in wide outer orbits, or small asteroid-sized objects in close orbits could possibly model these.

In any event, it is not clear how a planetary system could have formed around PSR B1828−11. This pulsar differs in two important respects from PSR B1257+12: evolutionary history and age. PSR B1257+12 is older by a factor of roughly 10^4 and is believed to have undergone a spin-up episode involving accretion of material from a binary companion, which subsequently evaporated under the influence of the neutron star. The planetary system might have formed during this sequence of events. PSR B1828−11, in contrast, is at a quite different evolutionary phase, having an age of only $\sim$100 kyr. It could be argued that any planets were formed around the progenitor star before the birth of the neutron star. However, a massive progenitor star with planets is unlikely to retain more than one of these planets in a Type II supernova explosion (Thorsett & Dewey 1993), and any which do survive are likely to end up with very eccentric orbits. It is conceivable that planets could have formed from the explosion debris.

The most likely possibility is free precession of the pulsar, which for a rigid neutron star will occur if the star is deformed so that its spin axis is not aligned with its angular momentum vector. This process would naturally cause the angle between the spin and magnetic axes to vary cyclically, possibly with harmonics. As well as causing modulation of the slow-down rate, it will yield periodic variations in pulse-profile morphology as the line-of-sight to the Earth passes through different cross-sections of the pulsar's radiation beam. The timescale for precession depends on the degree of deformation of the pulsar; to produce a periodicity of 1000 days, the deformation of a rigid-body neutron star would have to be approximately 5×10^{-9}, comparable with or smaller than that expected for a spinning neutron star (Goldreich 1970). For a realistic neutron star with a superfluid component and a rigid crust, the expected precession period depends on the relative angular momenta of the two and the coupling between them; in particular it appears that the mere existence of long-term precession would necessarily imply imperfect pinning of the superfluid vortices to the crust (Shaham 1977, Sedrakian, Wasserman & Cordes 1999).

If free precession is responsible for the effects seen in PSR B1828−11, it may be observable in other neutron stars as well. There have been previous suggestions (Cordes 1993, Suleymanova & Shitov 1994, D'Alessandro & McCulloch 1997) that free precession might be the cause of possibly correlated timing behaviour and profile shape changes in other radio pulsars, but it seems that the strongly periodic behaviour of PSR B1828−11 is unique among the several hundred now being observed. Another family of neutron stars, the anomalous X-ray pulsars, are known to display "wobbles" in their slowdown rates (e.g. Mereghetti 1995, Melatos 1999). Further observations of all classes of neutron stars may therefore help to shed light on the physics involved in the precession indicated by the behaviour of PSR B1828−11.

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