Evidence for Free Precession in the Pulsar B1642−03

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ABSTRACT

We present an analysis of the timing data of the pulsar B1642−03, collected over a span of 30 years between 1969 and 1999. During this interval, the timing residuals exhibit cyclical changes with amplitude varying from 15 ms to 80 ms and spacing of maxima varying from 3 to 7 years. Interpretation of these observed cyclical changes in terms of free precession suggests a wobble angle of about $0^\circ\!.8$.

Subject headings: pulsars: general — pulsars: individual (B1642−03)

1. Introduction

The pulsar B1642−03 was discovered more than 30 years ago (Huguenin & Taylor 1969) and is known to exhibit interesting timing behaviour. It has a period of 0.387 s and a spindown rate $1.78 \times 10^{-15}\ s\,s^{-1}$, indicating that it is a relatively young pulsar, with a characteristic age of $P/2\dot{P} \sim 3.4$ Myr.

Since the pulsar discovery, timing measurements were carried out almost continuously for 13 years between 1969 July and 1982 September at the frequency of 2388 MHz using antennas of the Deep Space Network of NASA (Downs & Reichley 1983; Downs & Krause-Polstorff 1986). From a timing analysis of the Jet Propulsion Laboratory (JPL) data, Cordes and Downs (1985) found that the timing residuals of PSR B1642−03 show oscillatory behaviour with an amplitude of about 15 ms. Subsequently it was revealed that PSR B1642−03 also exhibits periodic changes in the shape of the mean pulse profile with a period of about 1000 days (Blaskiewicz 1991). According to Cordes (1993), cyclical timing residuals and periodic changes in the shape can be explained by the precession model with a wobble angle $\theta_p \sim 0.5^\circ$. This interpretation implies that free precession yields pulse shape changes from wobbling of the beam, besides any wobble that is also manifested in timing residuals due to the spindown torque law.

In this paper we continue to investigate the timing behaviour of the pulsar B1642−03, analyzing the data collected for 30 years. The extension of the timing data span from 13 to 30 years has become possible on the basis of regular pulsar timing observations carried out at Jodrell Bank Observatory (JBO) in the UK, at Hartebeesthoek Radio Astronomy Observatory (HartRAO) in South Africa, and at Pushchino Radio Astronomy Observatory (PRAO) in Russia. The Jodrell Bank data were obtained in the wide frequency range 0.4 - 1.6 GHz and cover a span of 18 years between 1981 July and 1999 September. The HartRAO timing data obtained at 1.6/2.3 GHz cover a span of ∼14 years between 1985 November and 1999 March. The Pushchino data were obtained at 0.1 GHz and include the timing data between 1991 March and 1999 October and a separate observing session in 1984 September - December. Together, these provide a continuous data set collected for 30 years with a 1 yr gap between 1983 July and 1984 August. A timing analysis of these data reveals that the timing residuals of PSR B1642−03 exhibit cyclical behaviour over the entire time span of observations. The best explanation of the observed cyclical timing residuals is probably provided by the precession model. These results were published earlier, in part, in Shabanova & Urama 2000.

2. Observations

At Jodrell Bank, observations of the pulsar with the 76-m Lovell radiotelescope started in July 1981. Cryogenic receivers sensitive to the two hands of circular polarisation were used at frequencies centred on 408, 610, 1400 and 1600 MHz with observing bandwidths of 8 MHz at the lower two frequencies and 32 MHz for the two highest. Each observation typically consisted of six 1 minute sub-integrations. The profiles from these were added in polarisation pairs and then combined to provide a single total-intensity profile. This was then convolved with a template derived from a single high signal-to-noise ratio profile at the same frequency to give a time of arrival.

At HartRAO, the timing observations of the pulsar B1642−03 commenced in 1985 November and were performed with the 26-m radiotelescope at frequencies near 1.6 or 2.3 GHz, using the system described by Flanagan (1993). The observing bandwidth was 10 MHz. Each observation usually consisted of three integrations. Pulse arrival times were obtained from 12 minute on-line integrations of the pulsed signal sampled at 0.15 ms intervals, using a filter time-constant of 200 μs. The pulse was approximated by a Gaussian. Such Gaussian templates have a reference point, which was chosen to be the centre of the main component.

The pulsar timing observations at Pushchino Observatory were started in 1991 March using the BSA radiotelescope (Large Phased Array), making up a linearly polarized transit antenna that operated at 102.7 MHz until 1998 May, and at 111.3 MHz since 1998 November after the BSA reconstruction. A 32-channel receiver with a channel bandwidth of 20 kHz was used for the observations. The receiver time constant was 3 ms. Each measurement consisted of 3.6 minute integration of the pulsar signal, synchronized with the apparent pulsar period (Shabanova 1998). Observation time corresponded to transit time at the declination of the pulsar. The data consist of the mean pulse profiles recorded approximately three times a month. Pulse arrival times were derived by cross-correlating the mean pulse profile with a standard low-noise template.

The mean pulse profiles of the pulsar B1642−03 for a single observation at different observing frequencies are shown in Figure 1.

3. Timing analysis and results

The topocentric arrival times collected at JBO, HartRAO, and PRAO, and the geocentric arrival times obtained from the archival JPL timing data (Downs & Reichley 1983; Downs & Krause-Polstorff 1986), were all referred to the solar system barycenter at infinite frequency using a standard pulsar timing technique (Manchester & Taylor 1977). This involved the use of the JPL DE200 ephemeris and the position given by Downs & Reichley (1983), together with a proper motion equal to zero. A second-order polynomial describing secular spin-down pulsar behaviour was fitted to the barycentric arrival times to obtain residuals from a timing model. The timing residuals, derived as the observed times minus the predicted ones, were used for improving the astrometric and the spin-down parameters of the pulsar. Measured timing parameters are shown in Table 1. The period and the period derivative were determined from the entire interval of observations from 1969 to 1999 (fit interval MJD 40414 - 51450). Analysis of the timing residuals showed that the pulsar has a proper motion close to zero. Recent analysis of Martin (1999) confirmed that the proper motion is 12 ± 8 mas yr^{-1} and barely significant. The pulsar catalog (Taylor, Manchester, & Lyne 1993) quotes a proper motion obtained by Lyne, Anderson, & Salter (1982) as being much larger. However, their measurements have large errors and this, in principle, does not exclude a possibility that the proper motion may be zero. The observations of the pulsar in the range 0.1 - 1.6 GHz allowed us to determine the dispersion measure with high accuracy.

3.1. Timing residuals of PSR B1642−03

Figure 2 shows the timing residuals of PSR B1642−03 after removing the second-order polynomial from the combined JPL, JBO, HartRAO, and PRAO data set of the barycentric arrival times. As can be seen, the timing residuals for PSR B1642−03 exhibit oscillatory behaviour, and more than six cycles are observed over the entire 30 year data span. The central part of the residual curve has a 1 yr gap between 1983 July and 1984 August, but nevertheless, it gives adequate information. The curve presents fluctuations whose amplitudes initially increase and then fade. The amplitude of the cycles varies between 15 and 80 ms and the spacing of maxima varies between 3 and 7 years. It will be noticed that the larger amplitudes correspond to the larger spacings. The curve is asymmetric with respect to the X-axis.

The observed cyclical changes are atypical of most timing noise seen from radio pulsars. Most timing noise is consistent with red, stochastic noise that is aperiodic. The timing residuals from PSR B1642−03 are not strictly periodic, but are sufficiently cyclical that it is plausible to interpret them as the result of a wobble of the spin axis of the pulsar. Figure 2 demonstrates that the shape of the residual curve is robust against the particular length of the data set that is analyzed. The general character of the variations found earlier by Cordes & Downs (1985, their Fig.10l) for the interval 1969 - 1981 remained the same in our plot, despite the extension of our data span to 30 years.

3.2. Analysis of the spin-down parameters of PSR B1642−03

For a more detailed analysis of the variations, in Figure 3 we demonstrate changes of the spin-down parameters P and $\dot{P}$ versus time together with the timing residuals. The rotation period, P, and the period derivative, $\dot{P}$, were calculated from the local fits, performed over intervals of 200 days which overlapped by 100 days. The timing residuals shown in the lower plot were transformed into a uniform curve by averaging the residuals over 40 day intervals. The empty intervals were filled with numbers, derived by linear interpolation of average values of residuals taken from the nearest adjacent intervals. Such a procedure did not deform the initial curve, since the averaging time was considerably less than the timescale of cyclic changes. As is seen, the plotted period residuals, ΔP, and the period derivative residuals, $\Delta\dot{P}$, exhibit cyclical behaviour, and the observed variations in the period derivative $\dot{P}$ make up about 2% of the mean value of 1.78×10^{-15}. The variations in some cycles are similar in form, although these cycles do not exhibit a strict periodicity in their recurrence. Besides, the gap in the centre of these plots makes the picture of the changes incomplete. The variations in rotation parameters can cause the variations in the pulse shape of the pulsar. An analysis of the JBO data to discover long-term variations in the pulse shape showed no significant pulse profile changes. However, the precision of the measurements does not preclude the possibility of changes of the magnitude claimed by Blaskiewicz (1991). Any pulse shape changes at the low frequency of 0.1 GHz may not be noticed because the mean pulse profile has a simple shape.

In order to find periodicities contained in these time sequences, the power spectrum was computed using the Fourier transform. The results are given in Figure 4. There are two wide spectral features at around 0.0004 and 0.0008 day^{-1}, which are visible in the spectrum of all the three sequences. They have an identical amplitude in the spectrum of ΔP, whereas the spectrum of $\Delta\dot{P}$ exhibits more distinctly the second feature at around 0.0008 day^{-1} and the residual spectrum shows more clearly the first feature at 0.0004 day^{-1}. These spectral frequencies are multiple and correspond to the periods of 2500 and 1250 days, respectively. The features are wide because the timing residuals seen in Figure 2 are clearly not a strict periodic function of time. The spectral feature at around 0.00018 day^{-1} in the residual plot could be due to the envelope of the timing residual curve. The spectra of residuals $\Delta\dot{P}$ and ΔP also exhibit the feature at around 0.0015 day^{-1}, corresponding to the period of 667 days.

3.3. Analysis of multifrequency observations of the pulsar

Since 1991, the pulsar rotation has been monitored by JBO, HartRAO and PRAO; the timing residuals of PSR B1642−03 for these quasi-simultaneous observations in the frequency range 0.1 - 2.3 GHz are shown in Figure 5. The common span covers almost two cycles of the oscillatory timing residuals. Although the high- and low-frequency residual curves are similar in general form, at some phases of the cycle there is an appreciable time offset between the two different residual curves. The time offset is calculated by subtracting the low-frequency timing residuals from the high-frequency timing residuals averaged over about 40 days. This time offset is shown in Figure 5 (*bottom*) and has a weak quasi-sinusoidal variation with a maximum amplitude of $\sim$1 ms. This quasi-sine wave is, more or less, out of phase with the residual curve shown in Figure 5 (*top*). At the maximum of the timing residual curve, the 0.1 GHz pulses arrive $\sim$1 ms later than the pulses at high frequencies, and at the curve minimum the 0.1 GHz pulses arrive earlier than high-frequency pulses.

The 1 ms amplitude of the quasi-sinusoidal wave of the 0.1 GHz residuals may be interpreted in two ways. Firstly, it may arise from a change in dispersion measure of $\sim 2.5 \times 10^{-3}$ $pc\ cm^{-3}$. Alternatively, it may be interpreted as a result of changes in the time alignment of the low-frequency and high-frequency profiles during a cycle of the timing residuals. It is very plausible that the beam shapes are different at low and high frequencies, so that the timing residuals could have different shapes at the two frequencies.

4. Discussion

The pulsar B1642−03 is located above the Galactic plane with $b \sim 26^\circ$ and has a large uncertainty in the distance from the Sun. The pulsar catalog (Taylor, Manchester, & Lyne 1993) quotes the dispersion measure-derived distance of 2900 pc with an uncertainty of $\sim$ 50%. On the other hand, Prentice and ter Haar (1969) found for PSR B1642-03 a distance of about 160 pc, taking into account the presence of the HII region along the line of sight to this pulsar and its influence on the dispersion measure. Despite a large uncertainty in the distance, a small proper motion suggests that this pulsar is a low-velocity object. The observed value of $\mu = 0\overset{''}{.}002 \pm 0\overset{''}{.}007$ yr^{-1} implies a transverse pulsar velocity equal to 2 $km\ s^{-1}$ and 30 $km\ s^{-1}$ for an assumed distances of 160 pc and 2900 pc, respectively. This low-velocity pulsar has a Galactic z-distance of 70 pc and is inside the thin disk in which extreme Population I objects are born.

The most likely explanation for the cyclical timing residuals for the pulsar B1642−03 lies in the precession of a neutron star. The spin axis of an isolated pulsar can precess, if a neutron star has a nonspherical shape and its spin axis is not aligned with the symmetry axis. Free precession will cause a cyclical change in the angle α between the spin axis and the magnetic moment. The result will be cyclical variations in the spin-down torque acting on the pulsar and cyclical changes in the observed pulse profile because the observer will view the pulsar beam from different angles over the precession cycle (Pines & Shaham 1972; Shaham 1977; Nelson, Finn, & Wasserman 1990; Cordes 1993). Suggestions that the correlated timing behaviour and variations in the pulse shape might be related with the precessional effects were discussed earlier for some pulsars (Cordes 1993; Suleymanova & Shitov 1994; D'Alessandro & McCulloch 1997). A unique result was recently obtained for the pulsar PSR B1828−11 by Stairs, Lyne, & Shemar (2000). They reported the discovery of long-term, highly periodic, correlated variations in both the pulse shape and rate of slow-down of the pulsar PSR B1828−11. The authors explained these periodic changes by precession of a neutron star spin axis caused by an asymmetry in the shape of the pulsar.

In the case of PSR B1642−03, we observe long-term variations only in the timing residuals, and we do not see any profile shape changes in the range 0.1 - 1.6 GHz. Probably, the pulse shape variations were not detected due to cyclical character of the changes and their small magnitude. It should be noted that an analysis of the JPL data at 2.3 GHz done earlier by Blaskiewicz (1991) showed that the pulse shape of the pulsar has slight periodic changes in the brightness of the leading component with a period of about 1000 days. Therefore, the pulse shape changes do exist and their timescale agree well with our result. As was mentioned above, the spectral analysis of the period derivative residuals for PSR B1642−03 indicates the presence of a periodicity of about 1250 days. Therefore, the long-term variations in the pulsar rotation can be explained in terms of a free precession model, as was suggested earlier by Cordes (1993). The measured 1 ms quasi-sinusoidal time offset between the high- and low-frequency timing data over the cycle may also testify to its relationship to variations in the rotation of the pulsar.

In total, the spectra of the residuals for PSR B1642−03 exhibit a few wide spectral features at multiple frequencies at around 0.0002, 0.0004 and 0.0008 day^{-1} that correspond to the periodicities of approximately 5000, 2500 and 1250 days, respectively. Note that these are some preferred frequencies, as the strict periodic behaviour of PSR B1642−03 is absent. Nevertheless, the multiple character makes this result similar to the result obtained for the pulsar PSR B1828−11 (Stairs, Lyne, & Shemar 2000), the spectra of which for the residuals and the pulse shape parameter show harmonically related sinusoids with periods of approximately 1000, 500 and 250 days. The presence of the multiple frequencies in the spectra of the residuals may testify, by analogy with PSR B1828−11, that it is related to the precession of a neutron star spin axis. The observed variations for PSR B1642−03 in the period derivative $\dot{P}$ make up 1.7%. We may estimate corresponding changes in the angle α, using the vacuum dipole model, in which the slow-down rate $\dot{P} \propto \sin^2 \alpha$. Suggesting that $\alpha \sim 60^\circ$, the change of similar magnitude in $\sin^2 \alpha$ will give a variation in the magnetic inclination angle α of $0\overset{\circ}{.}8$. This value is very similar to that obtained by Cordes (1993).

Observations of the long-term cyclical variations in the pulsar spin for PSR B1642−03 may provide a valuable tool for investigating the problems of the neutron star structure. The occurrence of free precession in neutron stars is highly problematic because of the superfluid interior (Shaham 1977; Shaham 1986; Sedrakian, Wasserman, & Cordes 1999). Glitches which have been observed in several dozen, mostly young pulsars provide strong evidence that superfluid neutrons exist in neutron stars, and these are expected to damp out any free precession on timescales of several hundred precession periods. However the clear correlated changes in pulse shape and slowdown rate in B1828−11 and the observations presented here indicate that precession is indeed occurring. A model will have to be devised which allows for precession to survive, even in the presence of some superfluid vortices.

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Table 1. Observed Parameters of PSR B1642-03

Parameter	Value[a]
Period, P (s)	0.387688759475(4)
Period derivative, $\dot{P}$ (10^{-15} s s^{-1})	1.780527(10)
Epoch of period (MJD)	40414.1297
Right ascension, α (J2000)	16^h 45^m $02^s.045(3)$
Declination, δ (J2000)	-03° $17'$ $58''.35(10)$
μ_α (mas yr^{-1})	1(2)
μ_δ (mas yr^{-1})	2(10)
Dispersion measure, DM (pc cm^{-3})	35.737(3)

[a] Quoted errors are twice the formal standard errors and refer to the least-significant digit.

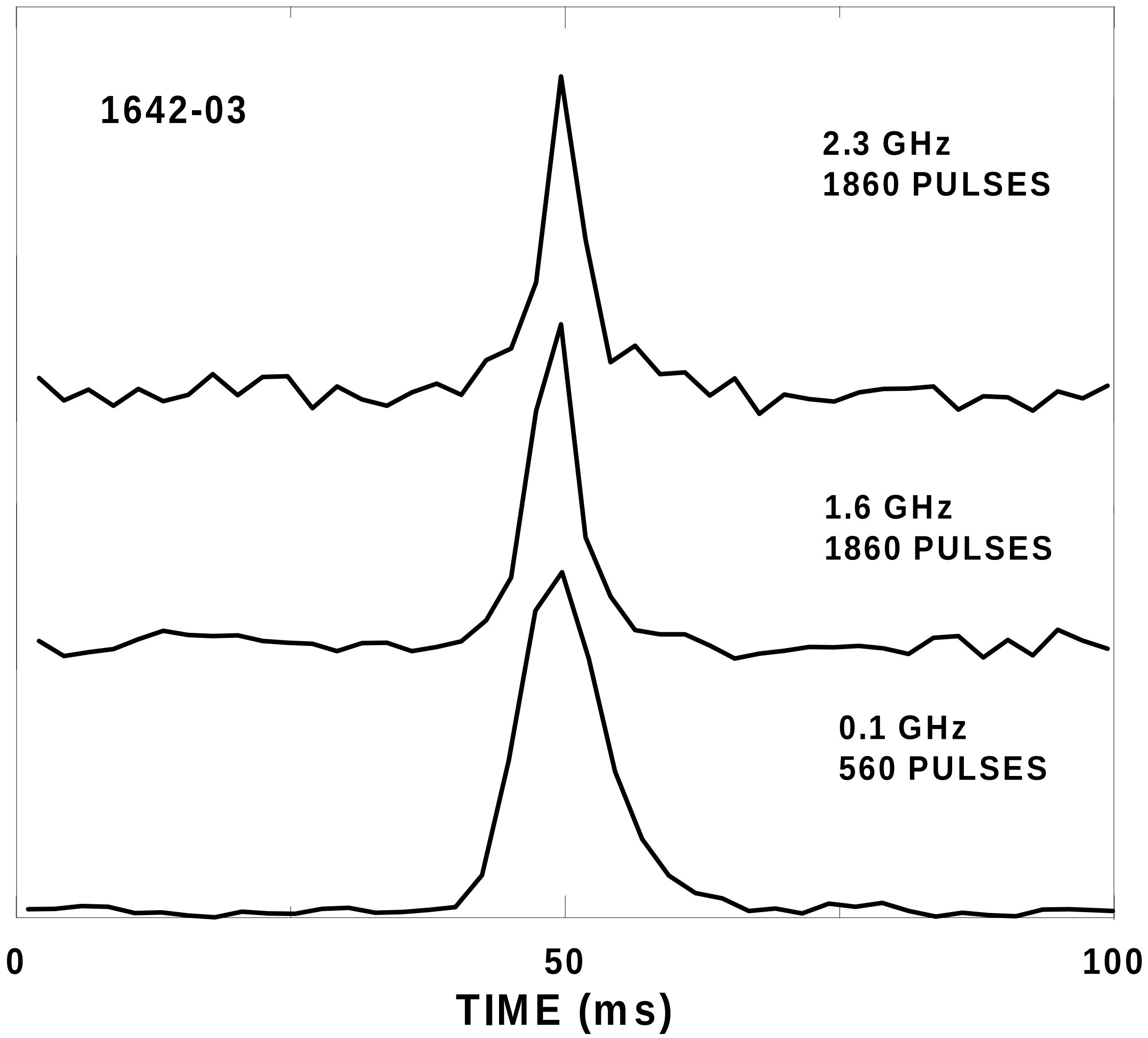

Fig. 1.— The mean pulse profile of the pulsar B1642−03 for a single observation at different frequencies of 0.1, 1.6 and 2.3 GHz. The alignment between the profiles is arbitrary.

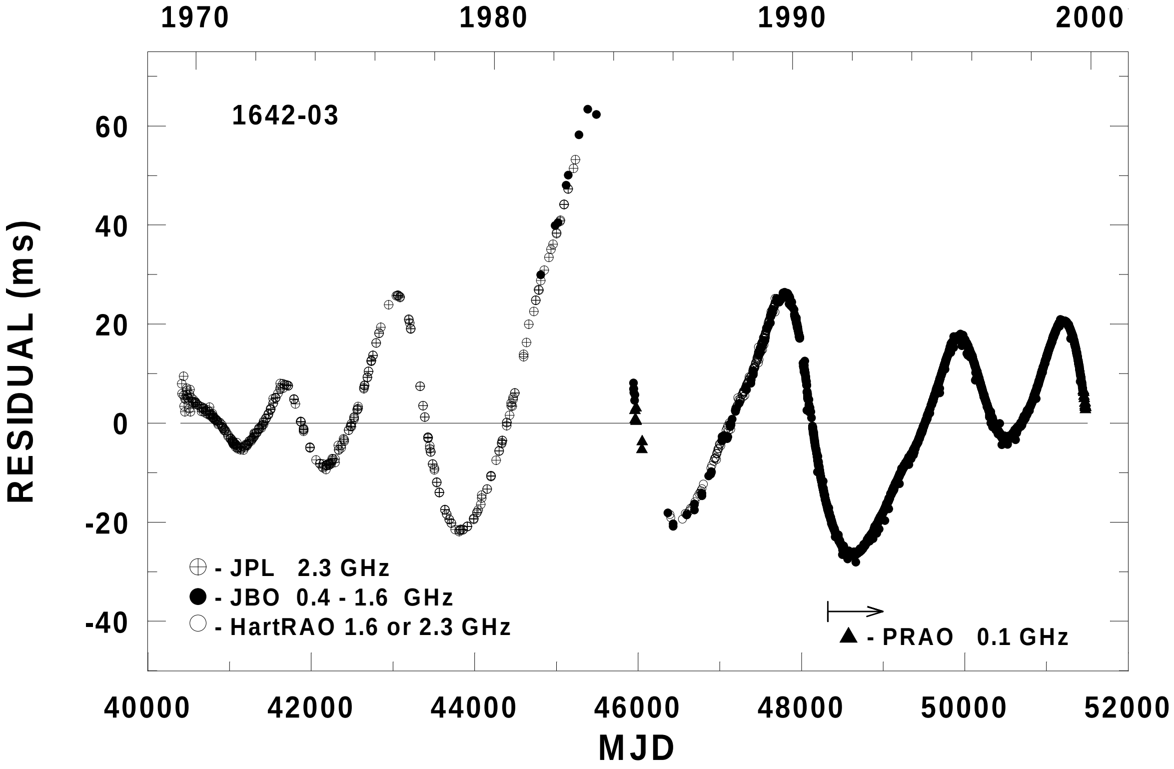

Fig. 2.— The timing residuals for PSR B1642−03 from the combined JPL, JBO, HartRAO and PRAO data set over the interval from 1969 to 1999.

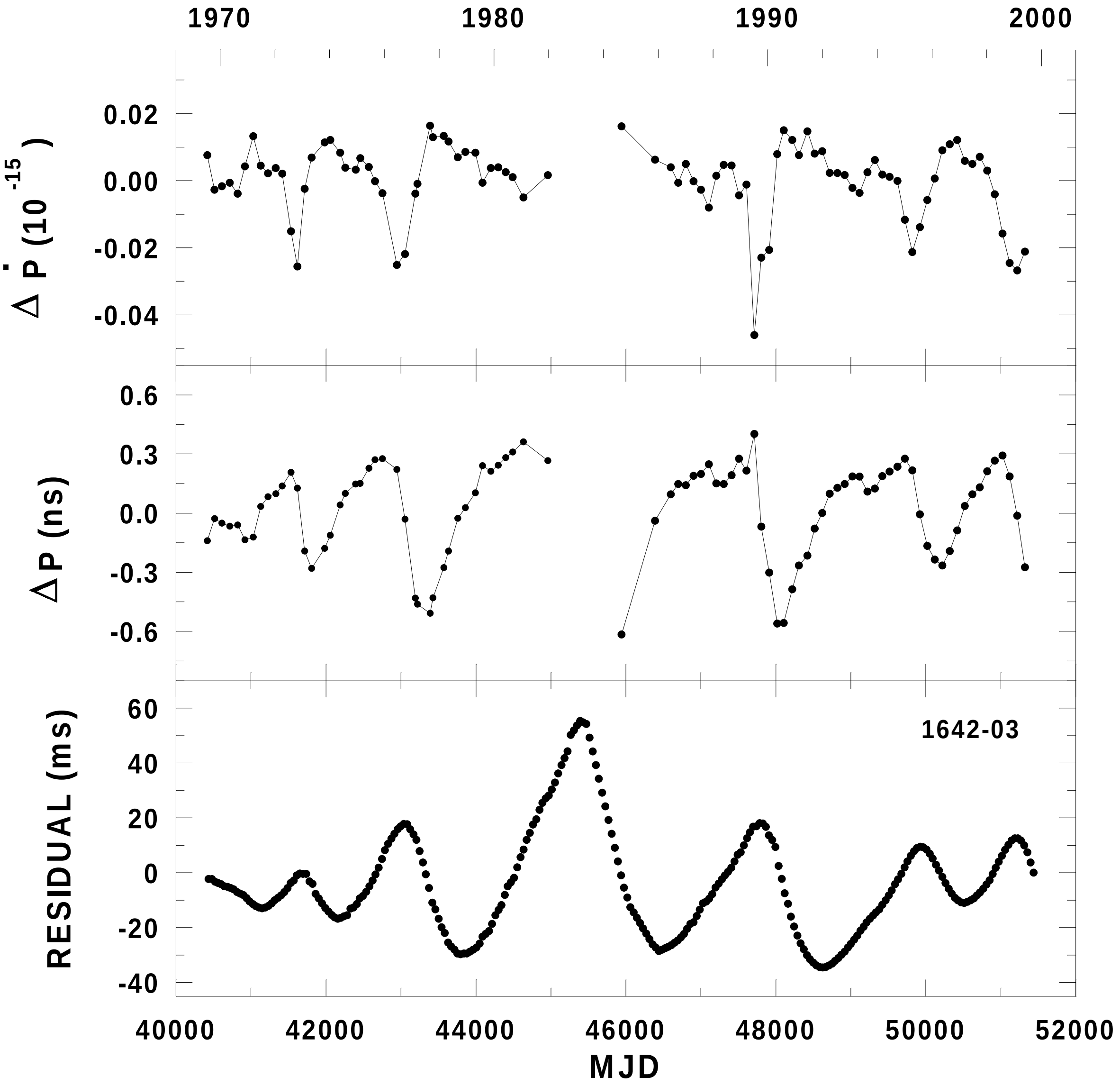

Fig. 3.— The period derivative residuals, $\Delta\dot{P}$, the period residuals, ΔP, and the timing residuals over 30 years of observations relative to the spin-down model given in Table 1.

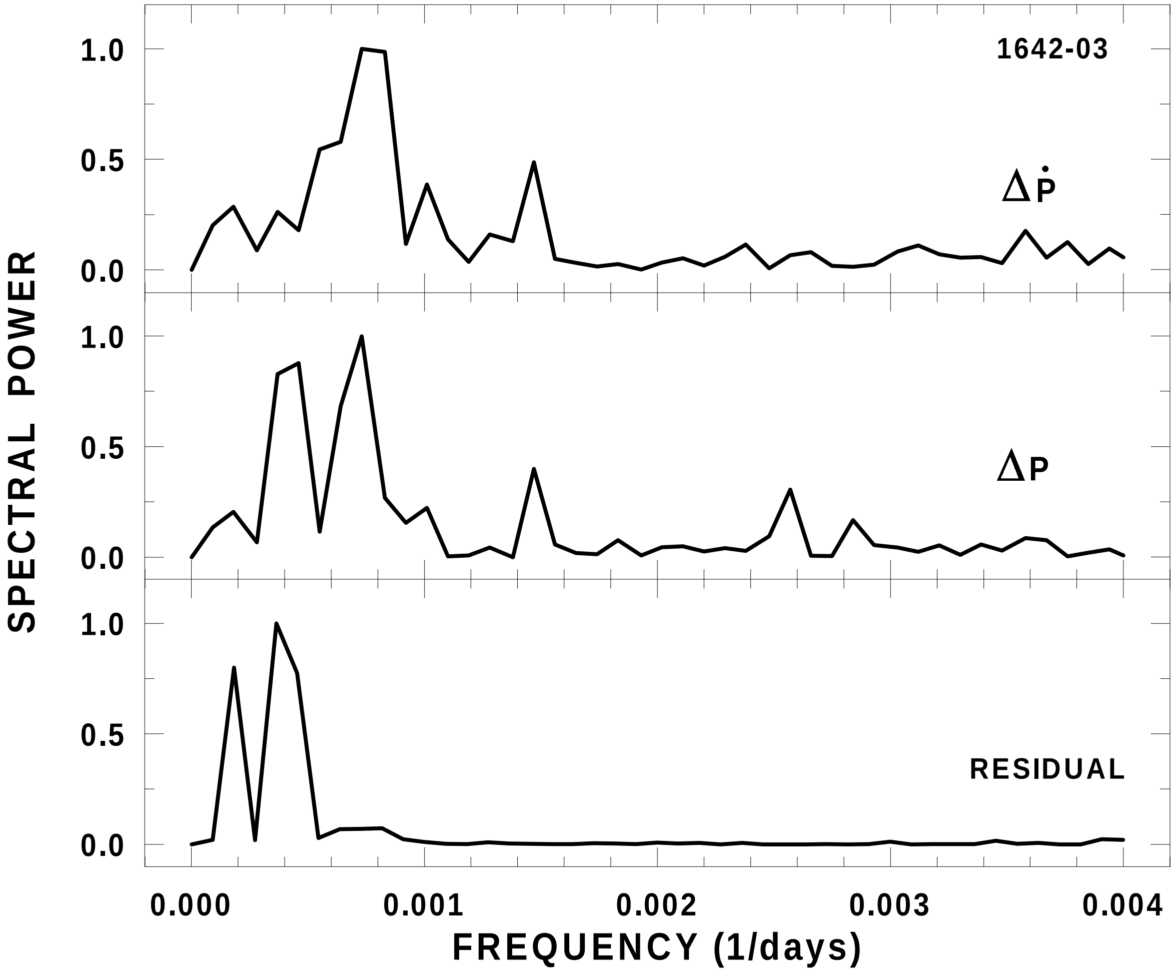

Fig. 4.— The power spectrum of the period derivative residuals, the period residuals and the timing residuals obtained by using the Fourier transforms tecnique. Spectral power of the residuals has arbitrary normalization. The spectra exhibit wide spectral features at multiple frequencies of approximately 0.0004 and 0.0008 day^{-1}, corresponding to 2500 and 1250 days respectively.

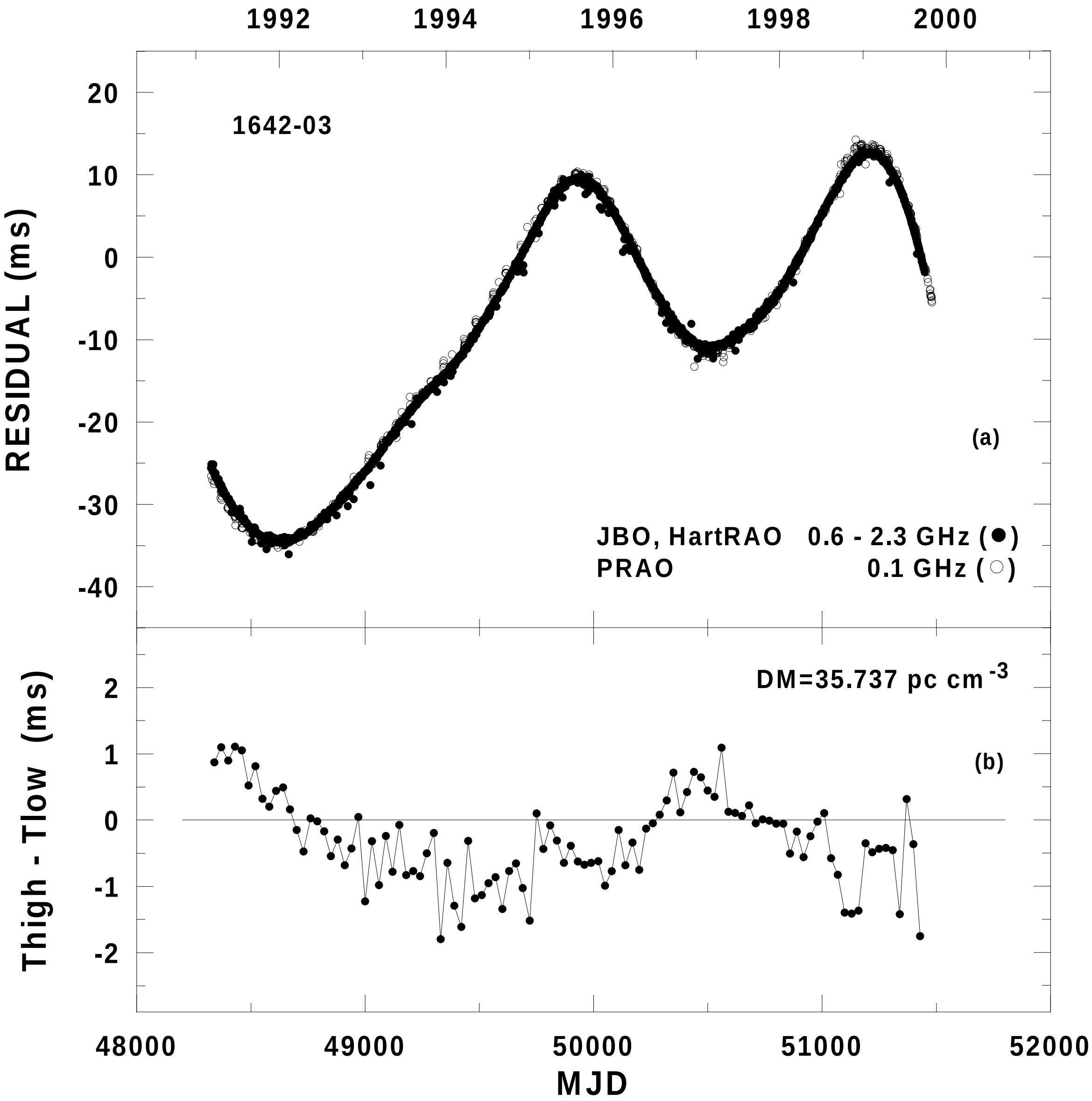

Fig. 5.— Top: the timing residuals of PSR B1642−03 between 1991 March and 1999 October. Bottom: the time-averaged differences in timing residuals obtained at high frequencies in the range 0.6 - 2.3 GHz and at the low frequency of 0.1 GHz.