Evidence of the long-term irregularities in the rotational frequency evolution of radio pulsars

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The results of the statistical investigation of dependence between the first (f1) and second (f2) derivative of the rotational frequency (f0) of "ordinary" isolated pulsars are reported. In this work the precise timing parameters for about 300 pulsars provided by several groups over the last few years are used. Most of the data is from the [ATNF] pulsars' database, and additional data is from [Chuckwude 2003] and [D'Alessandro et al. 1993]. The pulsars under investigation are: (i) with known f2 (accuracy of measurements is better than 75%); (ii) with rotational period P0 > 20 ms & its derivative P1 > 1.0e-17 s/s (to exclude recycling pulsars); (iii) non anomalous or binary. We analyse the correlation between f2 and f1 for the mentioned pulsars – separately the positive and negative branches of f2 as a function of f1 using f1–f2 diagram (Fig. 1). This diagram is consistent with the results of [Urama et al. 2006]. Also, the presence of correlation between modulus of f2 and f1 is confirmed [Lyne 1999]. This fact is widely accepted to be a result of the influence of pulsars' timing noise, which affects the secular (trend) value of f2 with a magnitude proportional to f1. Such hypothesis also explains the abnormally high pulsars' braking indices $n = f0*f2/f1^2$.

However, the high-precision measurements of f2 with large (6-30 years) time spans carried out recently for several hundreds of pulsars [Hobbs et al. 2004] gives the hint for an alternate interpretation. In our opinion the measured values of f2 reflect the secular evolution of the pulsars rotation on the several tens of years time scale. There are several arguments in favour of it:

(a) The timing noise is averaged within the observation time span. Indeed, the frequency and its derivatives undergo the irregular variations of significant amplitude. However, the observed characteristic time scales of these variations are from tens of days (microglitches) up to 2-5 years (most powerful glitches, precession and timing noise). It is clear that for a 10-30 year time span of observations the influence of such "small"-scale variations of parameters is very small and can not change it significantly because of averaging. For example, for PSR B1706-16 the variations of f2 with a 1.0e-24 s^{-3} amplitude has been detected on a several years time scale (see Fig. 5 in current poster – Fig.7 from [Hobbs et al. 2004]), with the value of f2 depending on the time interval selected. However, the fit over the entire 25 year time span gives a value of f2 = 3.8e-24 s^{-3} with a few percent accuracy. A similar fit over the 18 years for PSR B1540-06 gives a10% accuracy for the average f2 = 1.3e-26 s^{-3}, while the amplitude of its variations is 3.0e-25 s^{-3} on a 6 years time scale.

(b) There are several noise-less pulsars with large and negative f2. For 19 of 45 pulsars studied by [D'Alessandro et al. 1995] the timing noise is nearly absent (RMS < 0.001 P0). Six of them have f2 measured by [Hobbs et al 2004], which are well consistent with the |f2|–f1 correlation, i.e. anomalously high, and for three of them f2 < 0. On the Fig. 2 the f2–f1 diagram for noiseless (RMS < 0.001 P0) pulsars is plotted. It is clear, that pulsars' f2 value is uncorrelated with their timing noise magnitude.

(c) The change of second derivative between different epochs is uncorrelated with the noise level. The comparison of f2 values of 10 pulsars from [Chuckwude 2003] and [Hobbs et al. 2004] with the difference of measurement epochs T=2..6 years demonstrates the absence of any correlation between the timing residuals and the relative rate of the second derivative change T* f2/f2. So, it seems that the pulsar frequency second derivatives measured over the 10..30 years time spans reflect the secular evolution of the pulsar frequency rather than its irregular variations on the tens of days – years time scale.

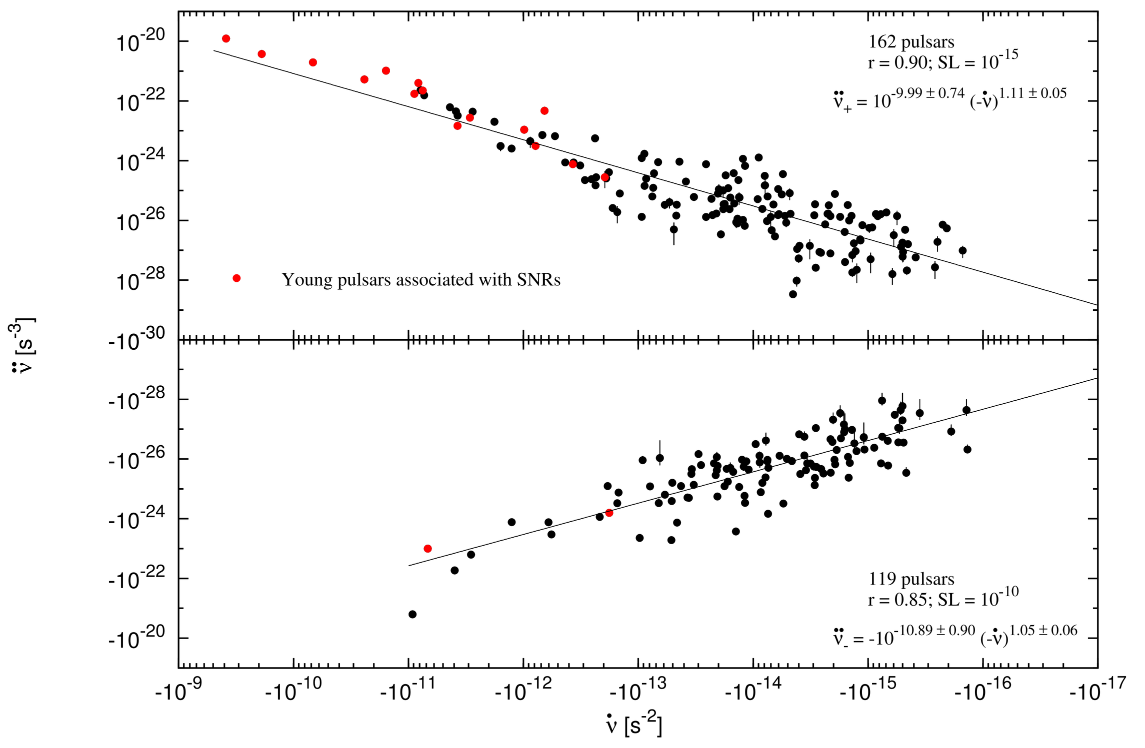

Fig. 1. f1-f2 diagram for the ~300 pulsars with known f2.

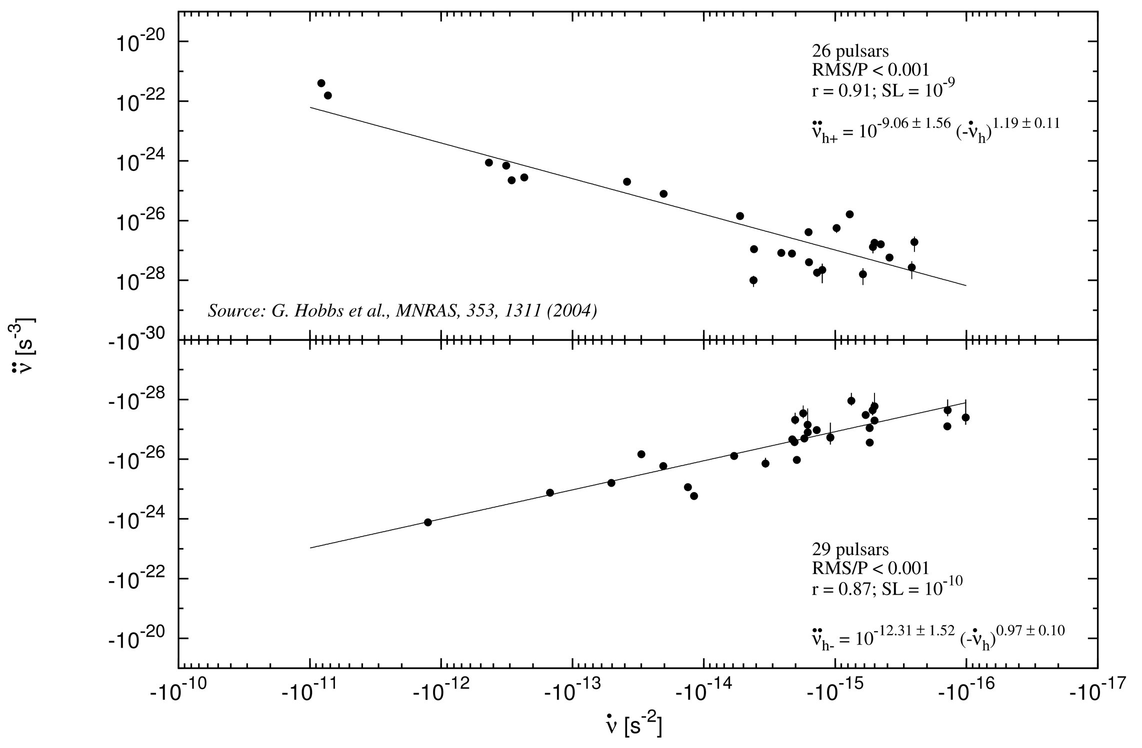

Fig. 2. f1-f2 diagram for the noiseless pulsars with RMS < 0.001

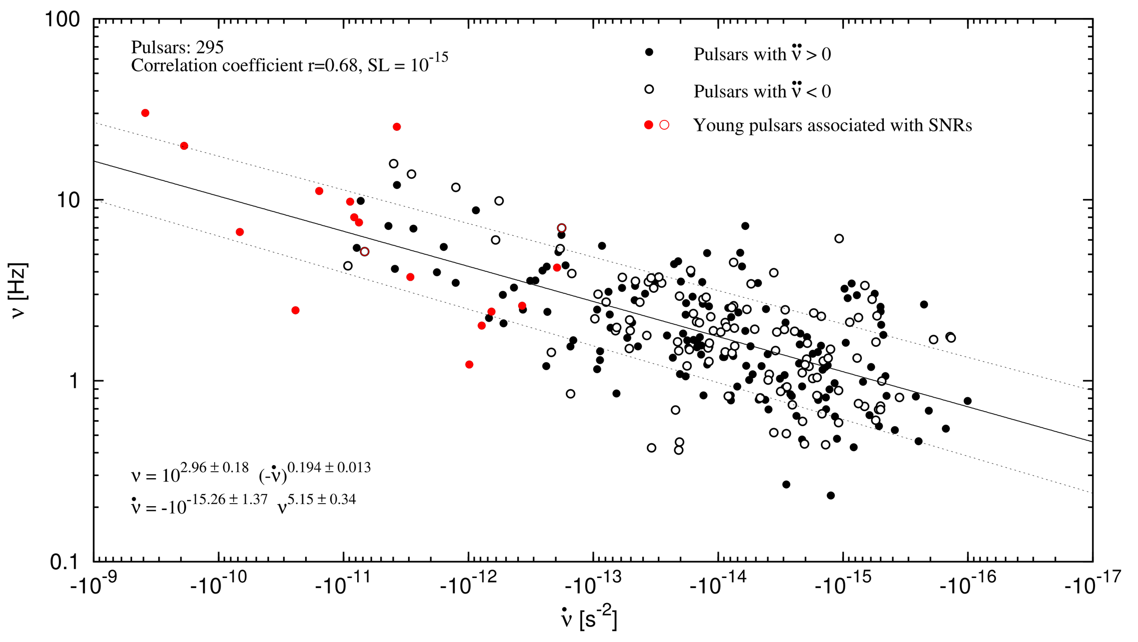

Fig. 3. f1-f0 diagram for the mentioned pulsars.

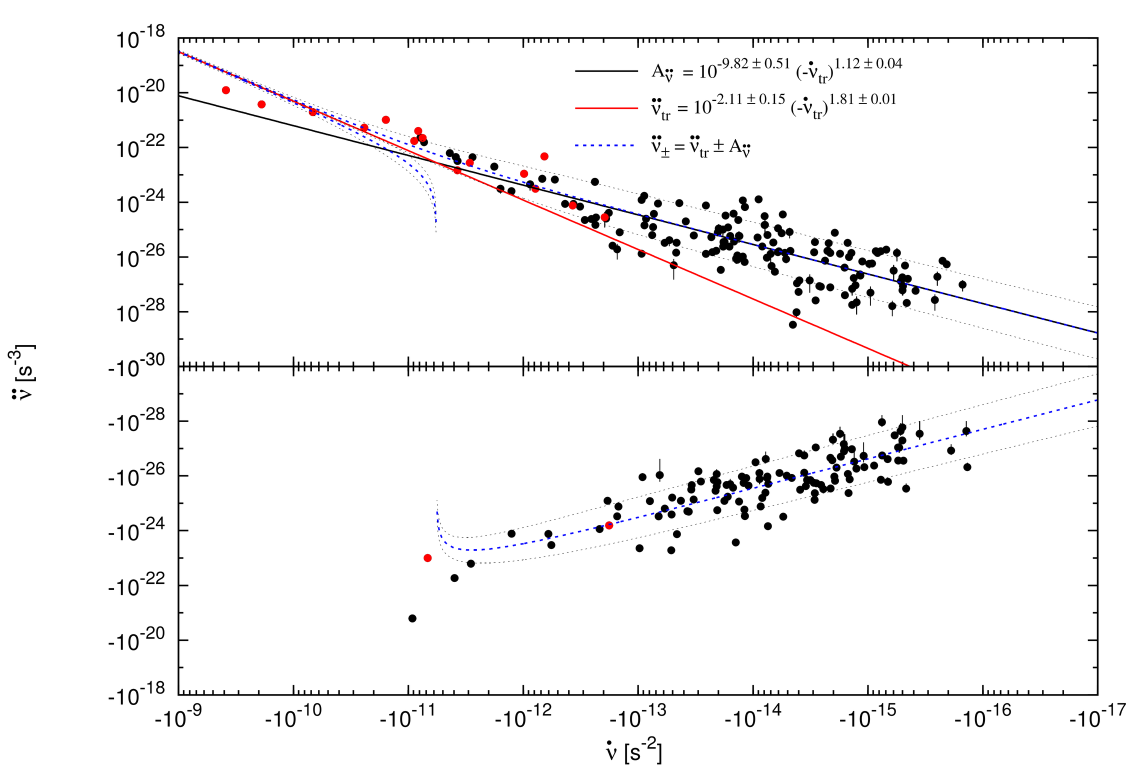

Fig. 4. Amplitudes of oscillating component and secular behaviour of f2 on f1-f2 diagram.

In the current work a certain positive asymmetry in the f2 distribution was found. Also, all younger pulsars associated with supernova remnants have the lowest f1. Hence, one can consider both branches of f1–f2 as evolutionary ones, independently from the sign of f2. Note that f1 is strongly correlated with the pulsars' characteristic age = *-0.5*f0/f1*. The pulsars with an all-time negative f2 must evolve with the decreasing of f1, but the diagram on Fig. 1 shows inverse behaviour! This way we have an explicit contradiction! Following up to the ideas above, this contradiction is easily solved by assuming the presence of a non-monotonic oscillating component of f0(t) superimposed with a secular one. Its key property is an "oscillating" nature, which leads to a zero mean value of the frequency and its derivatives, but with significant non-zero dispersions. It defines the amplitude of negative and positive branches on Fig. 1, and their asymmetry due to the presence of non-zero secular component of f2, corresponding to pulsar evolution with a "normal" value of braking index (as opposed to its measured values of $-10^6..10^6$ for branches).

The f1–f2 diagram for the reviewed ~300 pulsars was plotted (see Fig. 3). We found quite a strong correlation between these quantities, which does not depend on the sign of f2. Note that younger pulsars are located on the left side of the diagram, hence one can consider this distribution also an evolutional one. We determine secular (trend) braking index for considered pulsars: $n = 5.15 \pm 0.34$. This value may suggest the significance of multipole components in the pulsar's magnetic field, or the deviation of the angle between pulsar rotational and dipole axes from / Note that 4 youngest pulsars that have the biggest modulus of f1, have a braking index *n* even less than 3. Perhaps the secular spin-down law for the youngest pulsars differs from that of the older ones. Note, that the index of power in f1– empiric law is significantly different from the -1.0. We derived f1 ~ $^{-1.16 \pm 0.02}$. This fact is an additional argument in favour of the hypothesis of correlation between f0 and f1. And index of power -1.16 ± 0.02 is consistent with braking index n = 5.15 ± 0.34 in f0 – f1 law.

Let us summarize the properties of the pulsars behaviour presented on Fig. 1. The positive asymmetry in f2 distribution signifies a positive sign of the secular (trend) f2 values; the "lack" of pulsars in the region with f1 < -1.0e-11 s^{-2} is a consequence of the low amplitude of oscillating process for the young pulsars, where the positive secular f2 value, affected by oscillations has not changed its sign yet; and abnormally high braking indices are the result of domination of oscillating component in f2 over secular one.

Variations of the pulsar rotational frequency may be complicated – periodic, quasi-periodic, or completely stochastic. Generally, the evolution of f0 may be described as a superposition $f0(t) = f0_{tr}(t) + f0(t)$ where $f0_{tr}(t)$ describes the secular evolution of pulsar parameters according to "standard" spin-down with a small braking index, and f (t) are irregular variations. The latter satisfy the obvious conditions of zero mean values $< f0(t)>\sim< f1(t)>\sim< f2(t)>\sim0$ over the time spans larger than the characteristic time scale of the variations. The amplitude of the observed variations of f2 is related to the dispersion of this process as $A_{f2} = \ _{f2} = sqrt(< f2^2>)$.

The second derivative values on the upper $f2_+$ and lower $f2_-$ branches on Fig. 1 may be described as $f2_\pm(t) = f2_{tr}(t) \pm A_{f2}(t)$ due to the logarithmic nature of the plot. This equation describes some "average" pulsar, while the spread of points inside the branches reflects the variation of both amplitudes and phases over the pulsar ensemble. The second derivative is the only parameter significantly influenced by the variation, therefore $f0_\pm(t) \sim f0_{tr}(t)$ and $f1_\pm(t) \sim f1_{tr}(t)$. Using these relations the secular behaviour $f0_{tr}(t)$ (or, $f0_{tr}(f1_{tr})$) may be found by plotting the studied pulsar group on the f1–f0 diagram (Fig. 3). It is easily seen that the behaviour of these two pulsar sub-groups (f2 > 0 & f2 < 0) is the same, which is in agreement with the smallness of the pulsar frequency variations in respect to the intrinsic scatter of f0(f1). However, a strong correlation between $f0_{tr}$ and $f1_{tr}$ is seen. It is easy to get the relation between $f2_{tr}$ and $f1_{tr}$ from f0–f1 dependence, which is shown in Fig. 4 as a thick dashed line. The same relation may be also estimated directly by using the asymmetry of branches seen on Fig. 1 as simply a half-sum of branches fits. Such estimation, while being very noisy, is positive in the -1.0e-11.. -1.0e-15 s^{-2} range. The amplitude of the f2(t) oscillations, A_{f2}, may be easily computed in a similar way as a half-difference of the same fits. The result is shown in Fig. 4 as a solid line. The amplitude A_{f2} is decreasing almost linearly with the increase of $f1_{tr}$, i.e. pulsar age.

So, the statistical analysis of pulsars' frequencies and its derivatives allows us to determine both the secular behaviour of pulsars, and amplitude of the second derivative oscillations as a function of f1, and therefore, the pulsars' ages. The nature of the oscillation process may be either periodic, quasi-periodic, or purely random. For example, in the case of a simple periodic (harmonical) process it is possible to estimate its period (as a ratio |f2/f3,| known for a few pulsars), and therefore, the amplitude. Such a period is roughly 100..1000 years with the amplitude of f0 varies from 1.0e-10 Hz for young pulsars to 1.0e-03 Hz for older ones.

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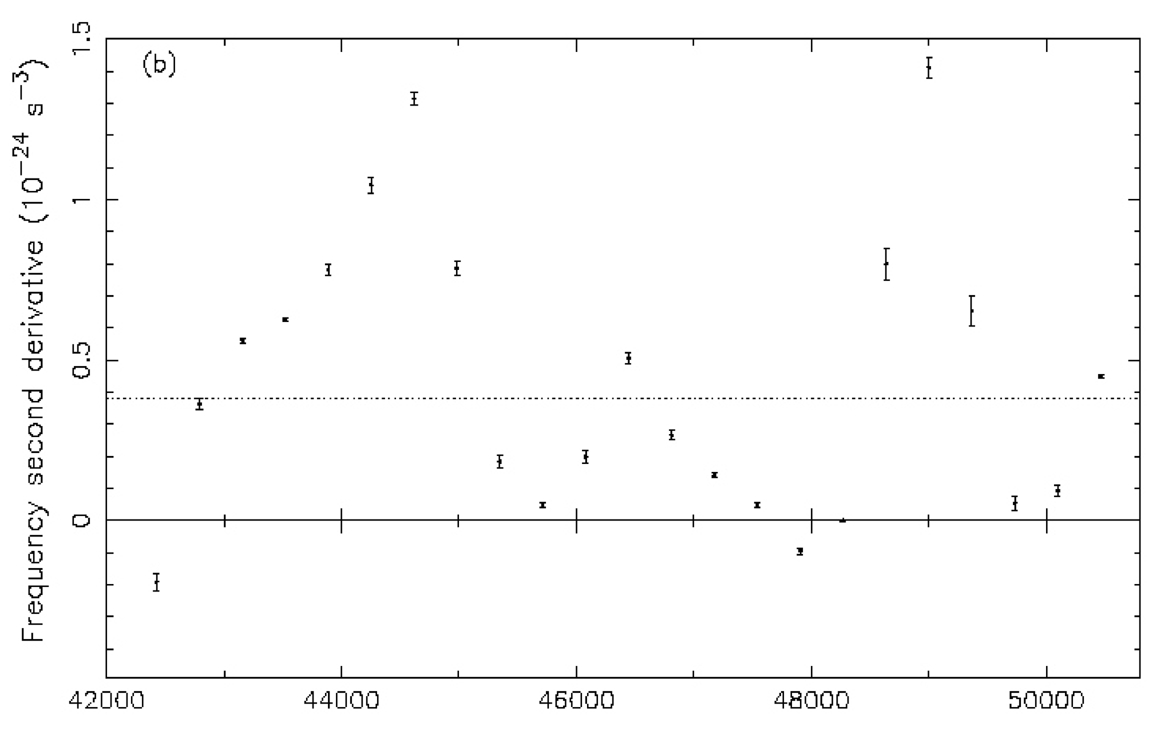

Fig. 5. Measured f2 values as a function of time for PSR B1706-16 using data spans of 6 yr, Figure from [Hobbs et al. 2004]

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