Recycled binary pulsars - a most precise laboratory of fundamental physics

G. S. Bisnovatyi-Kogan [a]

[a] Space Research Institute, Russian Academy of Sciences, Moscow, Russia

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis
Taylor & Francis Group

Recycled binary pulsars – a most precise laboratory of fundamental physics

G. S. BISNOVATYI-KOGAN*

Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32,
Moscow 117997, Russia

We discuss here the problems connected with radio pulsars in close binary systems, which have an anomalously small magnetic field and rotate very rapidly. The first discovered Hulse–Taylor binary pulsar permitted us to make the indirect discovery of gravitational waves. Later single recycled pulsars (RPs) that had been in binaries before the disruption of the pairs were found. The mechanism of the pair disruption and the formation of a single RP is considered on the basis of the mechanism of enhanced evaporation. General relativity effects in the pairs connecting two neutron stars (NSs) and, in particular, in a double-pulsar system are considered. Timing observations of NS + NS binary pulsars provide a unique means of checking general relativity and the variability of the gravitational constant.

Keywords: Recycled pulsars; Gravitation

1.   Introduction

The discovery of pulsars was first announced by Hewish *et al.* [1]. Until 1973 all known pulsars (more than 100) had been single, while more than half the massive stars (predecessors of pulsars) are in binaries. This gave the impression that pulsars avoid binary systems, although at least half of all ordinary stars enter binary systems. In the 7 years after the discovery of the first pulsar, it was assumed that the core-collapse supernova explosion, which forms a pulsar, leads to the disruption of the binary system or, for some reason, core-collapse supernovae completely avoid exploding in close binaries [2].

2.   Pulsars and close binaries

The X-ray satellite UHURU was launched in 1971, and shortly thereafter X-ray pulsars in binaries were discovered. One of the best studied is the X-ray pulsar Her X-1. It has a pulsation

*Email: bisnovatyikogan@gmail.com

period $P_p \approx 1.24$ s, an orbital period $P_{orb} \approx 1.7$ days, a neutron star (NS) with a mass of about $1.4\,M_\odot$, and an optical star with a mass of about $2M_\odot$ (see, for example, [3]).

It was shown by Bisnovatyi-Kogan and Komberg [4] that this system should give birth to a binary radiopulsar, for the following reasons.

(i) After 100 million years the optical star will become a white dwarf (WD), mass transfer will be finished, and the system will be transparent to radio emission.
(ii) The rotation of the X-ray pulsar is accelerating owing to accretion; so, after the birth of the WD, the NS will rotate rapidly, with $P_p \approx 100$ ms.

It was suggested in [4] that binary radiopulsars had not been not found until 1973, because the magnetic field of the NS decreases by a factor of about 100 during the accretion; so binary radiopulsars are very faint objects. The pulsar luminosity $L \propto B^2/P^4$; so, at small B, the luminosity L is low even on rapid rotation. The magnetic field is decreasing because of screening by the infalling plasma.

3. The Hulse–Taylor pulsar

Hulse and Taylor [5] discovered the first binary radiopulsar with a period $P_p = 0.05903$ s, an orbital period $P_{orb} \approx 7.75$ h and an orbit eccentricity $e = 0.615$. The properties of the first binary pulsar coincide with our predictions: rapid rotation together with a low magnetic field [6, 7]:

$$\dot{E} = -I\Omega\dot{\Omega} = I\left(\frac{2\pi}{P_p}\right)^2 \frac{\dot{P}_p}{P_p} = 2 \times 10^{33} \mathrm{erg s}^{-1},$$

$$B_p^2 = \left(\frac{3Ic^3 P_p \dot{P}_p}{8\pi^2 R_{NS}^6}\right)^{1/2} \approx 2.3 \times 10^{10} \mathrm{G}^2. \tag{1}$$

The average magnetic field of single radiopulsars is about 10^{12} G.

4. Disrupted pulsar pairs

Suggestions about the separation of pulsars at birth have been made by Bisnovatyi-Kogan and Komberg [4], where ten pairs of single pulsars with a possible origin from one pair were listed (table 1). The same idea was recently considered by Vlemming *et al.* [8], who measured the proper motions of pulsars. They suggested a common origin of the pair B2020 + 28 and B2021 + 51. It is interesting that one of these pulsars (B2020 + 28) had been suggested in [4] as the common origin with another pulsar (P2016 + 8, row 8 in table 1). The last pulsar is much closer to B2020 + 28 in the sky, and both are situated at the same distance [9]. The pulsar B2021 + 51 is much farther on the plane, and almost twice the distance, but the velocities intersect in the Cygnus OB association.

5. Recycled pulsar statistics

Recycled pulsars (RPs) are a separate class of NSs, containing more than 180 objects. All have passed the stage of accreting pulsars, accelerating the rotation and decreasing the magnetic

Table 1. Single pulsars of possible common origin.

Pair number	Pulsar designation	Positions Right ascension (h m s)	Declination (° ′ ″)	l^{II}	b^{II}	P_s (s)	Displacement (pc cm^{-3})	$\dot{P}$ ($\times 10^{-9}$ s day^{-1})	$\tau = P/\dot{P}$ (years)
1	P0943+10	09 43 20	10 05 33	225.4	43.2	1.098	15	–	–
	P0950+08	09 50 31	08 09 43	228.9	43.7	0.253	3	0.0198	3.5×10^7
2	P0809+74	08 09 03	74 38 10	140	31.6	1.30	6	0.014	2.5×10^8
	P0904+77	09 04	77 40	135.3	33.7	1.58	–	–	–
3	P1700−18	17 00 56	−18	4.0	14.0	0.802	≤40	0.154	6.9×10^6
	P1706−16	17 06 33	−16 37 21	5.8	3.7	0.653	25	0.55	3.3×10^6
4	P0329+54	03 29 11	54 24 38	145.0	−1.2	0.714	27	0.177	1.1×10^7
	P0355+54	03 55 00	54 13	148.1	0.9	0 156	55	–	–
5	P0525+21	05 25 45	21 55 32	183.8	−6.9	3.745 5	51	3.452	3×10^6
	P0531+21	05 31 31	21 56 55	184.6	−5.8	0.033 13	57	36.526	2.5×10^3
6	P1426−66	14 26 34	−66 09 94	312.3	−6.3	0.787	60	–	–
	P1449−65	14 49 22	−65	315.3	−5.3	0.180	90	–	–
7	P1845−01	18 45	−01 27	31.3	0.2	0.660	90	–	–
	P1845−04	18 45 10	−04 05 32	28.9	−1.0	0.598	142	–	–
8	P2016+28	20 16 00	28 30 31	68.1	−4.0	0.558	14.16	0.01	1.2×10^8
	P2020+28	20 20 33	28 44 30	68.9	−4.7	0.343	–	–	–
9	P2111+46	21 11 41	46 36	89.1	−1.2	1.015	141.4	–	–
	P2154+40	21 54 56	40 00	90.5	−11.5	1.525	110	–	–
10	P0611+22	06 11 10	22 35	188.7	2.4	0.335	99	–	–
	P0540+23	05 40 10	23 30	184.4	−3.3	0.246	72	–	–

field. So we have ordinary pulsars with $P_p = 0.033 - 8$ s and $B = 10^{11} - 10^{13}$ G and RPs with $P_p = 1.5 - 50$ ms and $B = 10^8 - 10^{10}$ G. These two groups are distinctly visible on the $P - \dot{P}$ diagram given in [10].

The number of RPs with NS + WD, and single RPs is about 180; the number of NS + NS pairs is 7 objects (such as the Hulse–Taylor pulsar) [10].

Single RPs (with a short P and a low B) have passed the stage of an X-ray pulsar in a binary and have later lost the companion WD. The NS + NS pulsars are situated in the galactic disc, and the NS + WD and single pulsars are mainly in the Galactic bulge, and in globular clusters (GCs).

6. Enhanced evaporation: formation of a single recycled pulsar

GCs contain about 0.001 of the mass of the Galaxy, and about half of the RPs. The formation of a binary in a GC may happen by tidal capture or triple collision. Disruption of the binary RP also happens by collisions with GC stars; most single RPs are situated in GCs. In the densest GC we have [10] 31 RPs in Terzian 5 (11 binary RPs and $10 + 10$? single RPs) and 22 RPs in 47 Tuc (14 binary RPs and $7 + 1$? Single RPs). In total, there are 80 RPs in the Galaxy (15 single RPs), and 108 RPs in GCs ($40 + 15$? single RPs).

Simple disruption of the pair by collisions with field stars does not work, because hard pairs become even harder by collisions. When a pair is in the state of disc accretion, with a WD filling its Roche lobe (figure 1 [33]), the situation is the opposite, and also hard pairs become softer during collisions owing to enhanced mass transfer; finally the pair is disrupted. This process, called 'enhanced evaporation' and first considered in [11], could explain the formation of a single RP in a GC, and their appearance in the bulge may be connected with full evaporation of a GC (see also [12]).
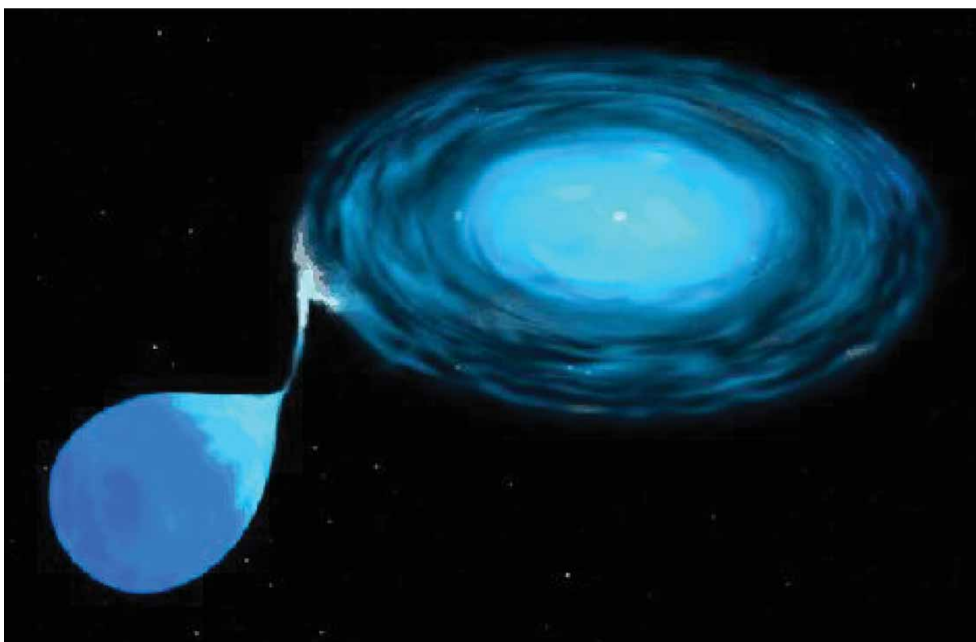

Figure 1. Artistic vision of disc accretion to the NS in X-ray sources [33].

7. General relativity effects: neutron star + neutron star

In the NS + NS binary, tidal effects are negligibly small; so several post-Keplerian general relativity effects have been measured from pulsar timing. They include [13] the parameter $\dot{\omega}$, which determines the rate of relativistic apse line motion, and the parameter γ, which represents the amplitude of the signal time delay due to the variable gravitational red shift and time dilation (the quadratic Doppler effect), when the pulsar moves in an elliptical orbit:

$$\dot{\omega} = 3T_{\odot}^{2/3} \left(\frac{P_{\text{orb}}}{2\pi} \right)^{-5/3} \frac{1}{1 - e^2} (M_A + M_B)^{2/3}, \tag{2}$$

$$\gamma = T_{\odot}^{2/3} \left(\frac{P_{\text{orb}}}{2\pi} \right)^{1/3} e \frac{M_B (M_A + 2M_B)}{(M_A + M_B)^{4/3}}. \tag{3}$$

The emission of gravitational waves results in the loss of orbital angular momentum and decreases the orbital period $\dot{P}_{\text{orb}}$:

$$\dot{P}_{\text{orb}} = -\frac{192\pi}{5} T_{\odot}^{5/3} \left(\frac{P_{\text{orb}}}{2\pi} \right)^{-5/3} \frac{1 + (73/24)e^2 + (37/96)e^4}{(1 - e^2)^{7/2}} \frac{M_A M_B}{(M_A + M_B)^{1/3}}, \tag{4}$$

The parameters r and s determine the time delay due to the Shapiro effect and are related to the companion's gravitational field:

$$r = T_{\odot} M_B, \tag{5}$$

$$s = x T_{\odot}^{-1/3} \left(\frac{P_{\text{orb}}}{2\pi} \right)^{-2/3} \frac{(M_A + M_B)^{2/3}}{M_B}. \tag{6}$$

Here, $T_{\odot} = GM_{\odot}/c^3 = 4.925\,490\,947\,\mu s$. The NS + NS RPs are the best laboratories for checking general relativity. The binary pulsar $1913 + 16$ timing has shown (indirectly) the existence of gravitational waves and resulted in the award of the Nobel Prize to Hulse and Taylor (1993).

8. A double-pulsar system

A binary system containing two pulsars with periods of 23 ms (J0737-3039A) and 2.8 s (J0737-3039B) was discovered by Lyne *et al.* [14]. This highly relativistic double-NS system allows unprecedented tests of fundamental gravitational physics [15]. A short eclipse of J0737-3039A by J0737-3039B was observed, and orbital modulation of the flux density and pulse shape of J0737-3039B, probably owing to the influence of the energy flux of J0737-3039A upon its magnetosphere [16]. These effects will allow the magneto-ionic properties of a pulsar magnetosphere to be probed. The observational properties of this system are listed in table 2.

9. Checking general relativity

Five equations in the system (2)–(6) contain two unknown masses. For correct gravitational theory, all curves on the (M_A, M_B) plane intersect at the same point. Three curves are available for the pulsar $1913 + 16$, and six curves for the double-pulsar system [15], where the additional line R follows from observations of both pulsars. All curves intersect at one point inside the

Table 2. Observed and derived parameters of the pulsars J0737-3039A and J0737-3039B. Standard errors are given in parentheses after the values and are in units of the least significant digit(s). The distance is estimated from the dispersion measured and a model for the interstellar free-electron distribution.

Parameter (units)	Value for the following pulsars	
	J0737-3039A	J0737-3039B
Pulse period P (ms)	22.699 378 556 138 (2)	2 773.460 747 4 (4)
Period derivative $\dot{P}$	$1.7596(2) \times 10^{-18}$	$0.88(13) \times 10^{-15}$
Right ascension α (J2000)	07 h 37 m 51.247 95 s (2)	
Declination δ (J2000)	$-30°$ 39' 40''.724 7 (6)	
Orbital period P_b (day)	0.102 251 562 8 (2)	
Eccentricity e	0.087 778 (2)	
Advance of periastron $\dot{\omega}$ (deg year^{-1})	16.900 (2)	
Projected semimajor axis $x = (a \sin i)/c$ (s)	1.415 032 (2)	1.513 (4)
Gravitational red-shift parameter γ (ms)	0.39 (2)	
Shapiro delay parameter $s = \sin i$	0.999 5 (4)	
Shapiro delay parameter r (μs)	6.2 (6)	
Orbital decay $\dot{P}_b (\times 10^{-12})$	-1.20 (8)	
Mass ratio $R = M_A/M_B$	1.071 (1)	
Characteristic age τ (Myears)	210	50
Surface magnetic field strength B (G)	6.3×10^9	1.6×10^{12}
Spin-down luminosity $\dot{E}$ (erg s^{-1})	5800×10^{30}	1.6×10^{30}
Distance (kpc)		≈ 0.6

error limits, indicating the correctness of general relativity at approximately the 0.4% level for pulsar 1913 + 16 after observations for about 20 years, and at approximately the 0.1% level after observations of the double system for 1 year.

10. Variability of the gravitational constant

For a long time [17–20] the possibility of the variation in the fundamental physical constants has aroused interest among physicists. While theories exist where these constants may vary [21–24], it is evident that only from experiments or, better, from astrophysical observations can we obtain a realistic answer. The spectral observations of distant quasars have been used to estimate the upper limits of the variations in the fine-structure constant, electron mass and proton mass [22].

Variations in the gravitational constant G have been measured by different methods [19], among which are investigations of stellar and planetary orbits. The combination of Mariner 10 and Mercury and Venus ranging gave the result [25]

$$\frac{\dot{G}}{G} = (0 \pm 2) \times 10^{-12} \, \text{year}^{-1}. \tag{7}$$

The Lunar Laser Ranging Experiment will last for many years and gave the estimations

$$\frac{\dot{G}}{G} = (0.4 \pm 0.9) \times 10^{-12} \, \text{year}^{-1} \tag{8}$$

for 2004 [26], and

$$\frac{\dot{G}}{G} = (6 \pm 8) \times 10^{-13} \, \text{year}^{-1} \tag{9}$$

for 2005 [27]. Incompletely modelled solid Earth tides, ocean loading or geocentre motion, and uncertainties in the values of fixed model parameters have to be considered in those estimations.

RPs now give the best available timing precision. Especially important results may be obtained from timing measurements of the pulsars in close binaries consisting of two NSs. These measurements have already been used for checking general relativity using B1913 + 16 [30] and J0737-3039 [14, 15]. From the long-time observations of the pulsar B1913 + 16, changes in the binary period have been measured and, explaining these changes by emission of gravitational waves, it was found [13] that 'Einstein's theory passes this extraordinary stringent test with a fractional accuracy better than 0.4%'. A similar accuracy was obtained from observations for only 1 year of the close binary consisting of the two pulsars J0737-3039A and J0737-3039B [14, 15]. Further observations of this system should considerably improve the precision, in comparison with that reached using the pulsar B1913 + 16.

The restrictions on the gravitational theory and checking its validity are possible because timing permits us to measure several quantities that give overlapping information. With the two masses as the only free parameters, the measurement of three or more post-Keplerian parameters over-constrains the system and thereby provides a test ground for the theories of gravity. In a theory that describes a binary system correctly, the post-Keplerian parameters produce theory-dependent lines in a mass–mass diagram that all intersect at a single point [15, 29]. Measurements of five relativistic parameters together with independent determination of the mass ratio, owing to the presence of the second pulsar, are available for pulsar J0737-3039, in comparison with only three parameters for pulsar B1913 + 16.

The variation in the fundamental constants could be incorporated in the general procedure of the timing data development. With six measurable quantities at present (and the possibility of increasing this number in the future [15]) the variability of several fundamental constants can be investigated.

Nevertheless, restrictions can be obtained for the variation in the gravitational constant using only the measurements of the variations in the binary period. The change in G has the most evident influence on the orbital motion, because only the emission of gravitational waves compete here with the variation in G. The influence of the variation in G on the pulsar period changes, star contraction with increasing gravity, or star expansion with decreasing gravity, accompanied by corresponding period changes at constant angular momentum, are strongly contaminated by the intrinsic changes in the rotational period due to losses of the rotational energy and angular momentum. The theoretical description of these losses is rather poor [30]. If we accept the correctness of general relativity inside the observed accuracy, then we can use the residuals (error box) of the measurements of the decay of the binary period $\dot{P}_b$ for the estimation of the variations in G. Such estimations were made first in [31] using timing data from [28], with the result

$$\frac{\dot{G}}{G} = (4 \pm 5) \times 10^{-12}\,\text{year}^{-1}. \tag{10}$$

More careful analysis of the data in [28] has been carried out in [32]. The influences of gravitational waves and variations in G on the binary period may be considered separately in a linear approximation owing to the smallness of both effects. The orbital angular momentum is conserved during slow G variations, as an adiabatic invariant; so only the total energy of the system is changing because of the change in the gravitational constant. The variations $\dot{P}$ and $\dot{e}$ have been obtained from variations of the Keplerian laws in the form [32]

$$\frac{\delta P_b}{P_b} = -2\frac{\delta G}{G}, \quad \frac{\dot{G}}{G} = -\frac{1}{2}\frac{\dot{P}_b}{P_b}, \quad \frac{\delta e}{e} = 0, \quad e = \text{constant}. \tag{11}$$

The first relation of equation (11), which was used in [31], was derived in a more complicated way. So, from measurements of the changes in the orbital period we may estimate variations in the gravitational constant, after taking into account the gravitational wave reaction. For the pulsar B1913 + 16 the error budget for the orbital period derivative, in comparison with the general relativistic prediction, has been given in [28].

Assuming that all deviations from general relativity are connected with the variation in G, we obtain the upper limit for these variations as follows [32]:

$$\frac{\dot{G}}{G} = (4.3 \pm 4.9) \times 10^{-12}\,\text{year}^{-1}. \tag{12}$$

Combination of the two results (12) and (7) permits us to narrow the range of G variations, which now may be situated in the following limits [32]: $\dot{G}/G$ is within the interval $(0.6, 2) \times 10^{-12}\,\text{year}^{-1}$. These limits are independent of the influence of the tidal interaction between the Earth and the Moon. Regretfully, the data on the measurements of $\dot{P}_b$ for the pulsar 1913 + 16 since 1993, as well as the refined data for the PSR J0737-3039, are not generally available, and the published [15] errors in the measurement of $\dot{P}_b$ in the last case are still considerably larger than those for the pulsar B1913 + 16 in 1993. Further observations of both pulsars could improve the precision in the estimation of the variations in G.

11. Conclusions

Our conclusions are as follows.

(1) The timing of the pulsars J0737-3039A and J0737-3039B is the most powerful instrument for the verification of general relativity due to the unprecedented precision of the observations.
(2) RPs are the most precise time standards available.
(3) The physics can be checked beyond the standard: G-variability.

Acknowledgement

References

[1] A. Hewish, S.J. Bell, J.D. Pilkington, *et al.*, Nature **217** 709 (1968).
[2] V. Trimble and M. Rees, in *The Crab Nebula*, IAU Colloquium 46, edited by R. D. Davies and F. Graham-Smith (Reidel, Dordrecht, 1970), p. 273.
[3] D.M. Scott, D.A. Leahy and R.B. Wilson, Astrophys. J. **539** 392 (2000).
[4] G.S. Bisnovatyi-Kogan and B.V. Komberg, Astron. Zh. **51** 373 (1974).
[5] R.A. Hulse and J.H. Taylor, Astrophys. J. Lett. **195** L51 (1975).
[6] J.H. Taylor, R.A. Hulse, L.A. Fowler, *et al.*, Astrophys. J. Lett. **206** L53 (1976).
[7] G.S. Bisnovatyi-Kogan and B.V. Komberg, Soviet Astron. Lett. **2** 130 (1976).
[8] W.H.T. Vlemmings, S. Chatterjee, W.F. Brisken, *et al.*, Pulsar astrometry at the microarcsecond level. Available online at: http://arxiv.org/astro-ph/0509025 (2005).
[9] A.G. Lyne and F. Graham-Smith, *Pulsar Astronomy* (Cambridge University Press, Cambridge, 1998).
[10] D.R. Lorimer, Binary and millisecond pulsars. Available online at: http://arxiv.org/astro-ph/0511258 (2005).
[11] G.S. Bisnovatyi-Kogan, Astrofizika **32** 313 (1990).
[12] G.S. Bisnovatyi-Kogan, Phys. – Usp. **49** 53 (2006).
[13] J.H. Taylor, Jr, Rev. Mod. Phys. **66** 711 (1994).
[14] A.G. Lyne, M. Burgay, M. Kramer, *et al.*, Science **303** 1153 (2004).

[15] M. Kramer, D.R. Lorimer, A.G. Lyne, *et al.*, Testing GR with the double pulsar: recent results. Available online at: http://arxiv.org/astro-ph/0503386 (2005).

[16] J. Arons, Relativistic shock waves and flow structure in relativistic winds, in *KITP Program: Physics of Astrophysical Outflows and Accretion Disks*, Kalvi Institute for Theoretical Physics, University of California, Santa Barbara, California, USA, 4 April–29 July 2005. Available online at: http://online.kitp.ucsb.edu.

[17] E. Milne, Proc. R. Soc. A **158** 324 (1937).

[18] P.A.M. Dirac, Nature **139** 323 (1937).

[19] J.-Ph. Uzan, Rev. Mod. Phys. **75** 403 (2003).

[20] H. Fritzsch, Lect. Notes Phys. **648** 107 (2004).

[21] Y.S. Wu and Z. Wang, Phys. Rev. Lett. **57** 1978 (1986).

[22] D.A. Varshalovich and A.Y. Potekhin, Space Sci. Rev. **74** 259 (1995).

[23] V.N. Melnikov, Int. J. Mod. Phys. A **17** 4325 (2002).

[24] K.A. Bronnikov, V.N. Melnikov and M. Novello, Gravitation Cosmol. **8** Suppl. II 18 (2002).

[25] J.D. Anderson, J.W. Armstrong, J.K. Campbell, *et al.*, Space Sci. Rev. **60** 591 (1992).

[26] J.G. Williams, S.G. Turyshev and D.H. Boggs, Phys. Rev. Lett. **93** 261 101 (2004).

[27] J. Mueller, J.G. Williams and S.G. Turyshev, Lunar laser ranging contributions to relativity and geodesy. Available online at: http://arxiv.org/gr-qc/0509114 (2005).

[28] J.H. Taylor, Classical Quantum Gravity **10** 167 (1993).

[29] T. Damour and N. Deruelle, Ann. Inst. H. Poincaré (Phys. Théor.) **44** 263 (1986).

[30] C. Michel, *Theory of Neutron Star Magnetospheres* (University of Chicago Press, Chicago, Illinois, 1991).

[31] V.M. Kaspi, J.H. Taylor and M.F. Ryba, Astrophys. J. **428** 713 (1994).

[32] G.S. Bisnovatyi-Kogan, Int. J. Mod. Phys. D **15** 1047 (2006).

[33] http://antwrp.gsfc.nasa.gov/apod/ap991219.html