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ABSTRACT

It is stressed that the timing data of binary pulsars are potentially rich of information about basic physics. The range of theoretical information that is in principle available go from yet unexplored aspects of relativistic gravity (e.g. gravitomagnetism, strong-field regime, inhomogeneous field equations) to some aspects of the nuclear interaction (equation of state) and even of unified theories of gravity (Kaluza-Klein, superstrings, ... ; through the measurement of the time-variation of Newton's gravitational constant). A convenient approach (the "parametrized post-Keplerian" formalism) for extracting, in the clearest possible way, a maximum amount of information from the timing data is sketched. The present observational results are reviewed.

1. INTRODUCTION

Immediately after the discovery in 1974 by Hulse and Taylor [1] of the binary pulsar PSR 1913+16, it was realized by many authors that this system was providing us with a new arena for studying relativistic gravitational effects. What was most exciting about it was the possibility to explore qualitatively new regimes of the gravitational interaction, that had not been probed by solar-system experiments. For instance, it was pointed out by several authors [2-7] that the "magnetic" aspects of gravity (which the Stanford gyroscope experiment [8] is trying to see in the solar system) might be detectable in the timing of binary pulsars. It was also pointed out that gravitational radiation reaction effects, though small, should be-come observable [3,9] as they would accumulate with time. Most importantly, the timing of a binary pulsar was offering our first possibility to test with precision the strong gravitational field regime. Indeed, as a pulsar is a neutron star, i.e. an object which condenses a mass comparable to that of the sun within a radius of the order of 10km, we are sure that, in a binary pulsar system, there are regions of strong gravitational fields, in the sense that the usual dimensionless parameter used in the solar system to measure the strength of the gravitational field, $G(\text{mass})/c^2(\text{radius})$, is no longer small but becomes comparable to one : $GM_\odot / c^2(10\text{km}) \simeq 0.15$. In this contribution we shall discuss some of the recent progress in the theory of the motion and timing of binary systems containing strongly self-gravitating bodies, and point out that several important tests of basic physics (gravitational physics, but also nuclear physics and unified theories of gravity) can, in principle, be extracted from the timing data of binary pulsars.

2. MOTION AND TIMING OF STRONGLY SELF-GRAVITATING BODIES.

The discovery of PSR 1913+16 has spurred many researches on the relativistic problem of motion. The most complete results have been obtained for the motion of two strongly self-gravitating bodies within Einstein's theory of gravity. The equations of motion, complete up to the gravitational radiation reaction level, have been derived [10] and solved [11]. And the corresponding observable effects in the timing of binary pulsars have been worked out [12]. This work has proven that the formulae that had been heuristically used after the discovery of PSR 1913+16 to predict the effects of gravitational radiation reaction in the timing are indeed consequences of the general relativistic dynamics of two strongly self-gravitating bodies. In particular, it is a remarkable feature of Einstein's theory of gravity that the fact that one is dealing with strongly self-gravitating bodies, though important in the derivation of the dynamics and timing, is "effaced" in the final result [13] (in the sense that all strong-field effects can be absorbed into the definition of two "Schwarzschild" masses, so that the final formulae look the same as for two weakly-self-gravitating bodies). This property of effacement does not hold in most other relativistic theories of gravity [14-16].

3. THE PARAMETRIZED POST-KEPLERIAN (PPK) APPROACH TO BINARY PULSAR DATA ANALYSIS.

The analysis of the numerous gravitational experiments performed in the solar system during the decades 1960-1980 has been greatly helped by the simultaneous development of a convenient theoretical framework : the so-called "parametrized post-Newtonian" (PPN) formalism. The first idea of the PPN formalism dates back to Eddington [17]. It was studied in the primitive Eddington form by Robertson [18], and, later, extended, refined and developed by Nordtvedt and Will [19-21,16]. The PPN formalism consists essentially in parametrizing the solutions of a general class of gravitational field equations by means of a finite set of (real) parameters. Then, this "universal" parametrized solution is used to predict the outcome of many different experiments. What makes possible to use a finite set of parameters to describe the solutions of a wide class of theories (i.e. a wide class of partial differential equations) is the quasi-stationary-weak-field nature of the gravitational field in the solar system. This allows one to use the so-called post-Newtonian expansion scheme. The use of this scheme means, roughly speaking, that one is only considering the behaviour of the theories in a small (functional) neighbourhood of the flat-space solution. The PPN parametrization is then seen as being similar to parametrizing the general class of C^2 functions, considered in a neighbourhood of the origin, by means, say, of a parabolic approximation : $f(x) = \alpha + \beta x + \gamma x^2$.

By contrast, as the motion, and timing, of binary pulsars involves strong-field effects, it poses the interesting theoretical challenge of generalizing the PPN formalism to the strong-field regime of relativistic gravity. Although it seems desperate to find an all-purpose strong-field generalization of the PPN approach, the combined work of Eardley [14], Will [15-16] and Damour and Deruelle [12] shows the existence of a substitute to such an ideal parametrized strong-field formalism : the "parametrized post-Keplerian" (PPK) formalism [22]. This formalism is based on the result that the theoretical formula predicting the arrival times of a binary pulsar (including strong-field and propagation effects) has a "universal" structure (valid for a wide class of relativistic theories of gravity) which can be parametrized by a finite set of parameters. This universal theoretical "timing formula" gives the arrival time of the N^{th} electromagnetic pulse at the barycenter of the solar system as :

$$t_N^{\mathrm{bary}} = F(N; p_1, p_2, \ldots), \tag{1}$$

where the (theory-independent) function F is obtained by eliminating the intermediate variables T and u between

$$N = N_0 + \nu T + \frac{1}{2}\dot{\nu}T^2 + \frac{1}{6}\ddot{\nu}T^3, \tag{1a}$$

$$u - e_T \sin u = 2\pi T/P + \mathrm{const.}, \tag{1b}$$

$$\begin{aligned} t_N^{\mathrm{bary}} =& x \sin\omega \left[\cos u - e_T (1 + \delta_r)\right] + x \left[1 - e_T^2 (1 + \delta_\theta)^2\right]^{1/2} \cos\omega \sin u + \gamma \sin u - \\ & - 2r \log\left\{1 - e\cos u - s\left[\sin\omega(\cos u - e) + (1 - e^2)^{1/2}\cos\omega\sin u\right]\right\}, \end{aligned} \tag{1c}$$

where

$$\omega = \omega_0 + 2k \tan^{-1}\left[(1+e)^{1/2}(1-e)^{-1/2}\tan u/2\right], \tag{1d}$$

$$e_T = e_0 + T\dot{e}_0, x = x_0 + T\dot{x}_0, P = P_0 + \frac{1}{2}T\dot{P}_0. \tag{1e}$$

Of particular interest among the parameters, $p_1, p_2, \ldots$, appearing in equations (1) are the "dynamical" orbital parameters which can be divided into

3 "Keplerian" parameters : x_0, e_0, P_0, and

8 "post–Keplerian" parameters : $\dot{x}_0$, $\dot{e}_0$, $\dot{P}_0, k, \gamma, r, s, \delta_\theta$.

4. TESTING BASIC PHYSICS WITH BINARY PULSAR DATA.

Within the framework of any relativistic theory of gravity, each of the post–Keplerian parameters, p_i^{PK}, will be expressible as a (theory–dependent) function of the Keplerian parameters and of 2 unknown "masses" (in general one must also assume some equation of state, although in General Relativity the effacement property makes this unnecessary for most of the parameters). In different theories of gravity, the latter functions,

$$p_i^{PK} = f_i^{THEORY}(m_1, m_2 \text{ ; Keplerian parameters ; equation of state}), \quad (2)$$

will, in general, markedly differ because of the strong-field effects linked with m_1, the mass of the pulsar, (and m_2, if the companion is also strongly self-gravitating). In other words, the measurement of (the Keplerian and of) n post-Keplerian parameters will determine in the 2-dimensional mass plane n curves whose shape and position strongly depend on the theory of gravity considered. If one is using the correct theory of gravity (and if the system is "clean", i.e. well represented by a simple theoretical model) these n curves should meet in one point. Therefore, the measurement of n PK timing parameters yields n-2 tests of the relativistic law of gravity (and, more generally, of the other ingredients of the theoretical model of the system). Note that, to get a test, one needs to combine the measurements of at least 3 PK parameters (besides the Keplerian parameters), and that each such test will probe simultaneously all the theoretical effects entering into the three concerned PK parameters. To see the wide range of theoretical information potentially present in binary pulsar timing we list below some of the effects playing a role in the 8 PK parameters appearing in the timing formula (1) above :

. propagation properties of the gravitational field [23] : in $\dot{P}_0$, $\dot{e}_0$, $\dot{x}_0$ [3,9,11,14-16].

. strong gravitational field effects : in essentially all the PK parameters [13-16].

. gravitomagnetic effects : in k [24], $\dot{e}_0$ and $\dot{x}_0$ [7,12] (gravitomagnetic effects induce both a "true" time variation of x through the spin-orbit-induced change of the inclination of the orbital plane, and "apparent" time variations of x and e_T through aberration effects, see Refs 12 and 24 for details and references ; gravitomagnetic effects can also be seen in the change of shape and polarization of the electromagnetic pulses [2-7]).

. high-order nonlinear and relativistic effects : in k [24].

. test of the inhomogeneous field equations and of the equation of state at supranuclear densities (through the measurement of the moment of inertia of a neutron star) : in k and $\dot{x}_0$ [24].

. space-variation of Newton's gravitational constant : in $\dot{P}_0, \gamma$ [14-16], ...

. time-variation of Newton's gravitational constant : in $\dot{P}_0$, $\dot{x}_0$ [25] ($\dot{G}$ is one of the few experimental handles on unified theories of gravity [26]).

At present, the best test obtained by the precise timing of PSR 1913+16 comes from combining the measurements of k, γ and $\dot{P}_0$ [27-32]. It probes propagation and strong-field properties of the gravitational interaction at better than the 2 % level [31-32],

$$\frac{\dot{P}_0^{obs}}{f^{GR}(k^{obs},\gamma^{obs})} = 1.007 \pm 0.017, \tag{3}$$

and yields an interesting estimate (consistent with zero) of the present value of $\dot{G}/G$ [25] :

$$\dot{G}_0/G_0 = (1.0 \pm 2.3) \times 10^{-11} yr^{-1}. \tag{4}$$

Not only does the $(k, \gamma, \dot{P})$-test fully confirm the ability of Einstein's theory to describe strong and rapidly varying gravitational fields, it also discriminates General Relativity from many alternative theories of gravity which are indistinguishable in the weak-quasi-stationary-field regime probed by solar experiments [14-16].

Recent observational work on post-Keplerian timing effects [29,30] has yielded a further confirmation of the timing model (through the $\sim 5\%$ measurement of "sini" in the way advocated in Refs. 33 and 34). However the significance of this result as a test of relativistic theories of gravity is not clear because the presently achieved "sini"-measurement coherently combines, in a theory-dependent way, several PK parameters. Let us mention also that the measurement of the periastron advance parameter k has recently reached the level $(\delta k/k \sim 2.10^{-5})$ where it becomes necessary to take into account higher-order relativistic contributions when using this measurement as an astrophysical tool for measuring the total mass $m_1 + m_2$ [24].

Further progress in "binary pulsar experiments" can come from two directions : (1) an improvement in the timing precision of the presently known best binary pulsar, PSR 1913+16 (such an improvement could lead to several qualitatively new tests of a large class of relativistic theories of gravity [35]), or (2) the discovery of other "relativistic" binary pulsars. The recent discovery of PSR 0021-72A, a fast-spinning binary pulsar in a short-period eccentric orbit [36,37], raises the hope of having a second "laboratory" for investigating some of the effects listed above. In particular, as the very small inclination of the orbital plane on the plane of the sky hints at a non-alignment of the spin-axis of the pulsar with the orbital momentum axis, several gravitomagnetic effects (yet unobserved in PSR 1913+16 probably because of the alignment $\vec{S}_1//\vec{L}$) might be detectable (especially the "true" secular change of x [37]). Let us mention also that the fact that the companion of PSR 0021-72A is probably a white dwarf, and not a neutron star (which obliges one to use a theoretical model of the system taking into account extension effects) makes it desirable to aim at measuring at least two "quasi-periodic" PK parameters (γ and r should be the easiest ones to measure), in order to get an estimate of the two masses independent of the model-dependent one furnished by interpreting the measurements of say (k,γ), $(k,\dot{x})$ or $(k,\dot{P}_0)$, which comprise "secular" PK parameters.

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