GENERAL RELATIVITY AND EXPERIMENT : A BRIEF REVIEW

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Our scientific knowledge of gravity arose from the combination of experimental facts and theoretical reasonings woven by Galileo. In particular, Galileo noticed the importance of the fact that all (test) bodies, released from rest, fall in exactly the same way in an external gravitational field. The paradigmatic verification of this fact by the dropping of various bodies from the leaning tower of Pisa is probably a myth, but the later pendulum experiments of Newton have verified the universality of free fall with an accuracy of one part in a thousand. Moreover, Newton emphasized the need to test that this property holds true not only for laboratory bodies, but also for celestial bodies. He suggested various ways of testing this in the solar system [1], and even claimed that Jupiter satellites data verified it with an accuracy of one part in a thousand. In reality the latter claim of Newton was flawed (see section 6.6 of [2]), but his idea was later vindicated by Laplace, and has been revived, within a modern context, by Nordtvedt [3] (this idea was recently extended to binary pulsar systems in Ref. [4]). In the modern terminology this foundational property of the gravitational interaction is also called the Equivalence Principle, because the theoretical interpretation of the universality of free fall is that the inertial mass m_i and the gravitational mass m_g of a body are exactly proportional and can be regarded as equivalent measures for a single physical property, *mass*. The equivalence $m_i = m_g$ is termed the weak equivalence principle when it concerns laboratory bodies, and the strong equivalence principle when it concerns celestial, i.e. from the modern perspective self-gravitating, bodies (see in the latter respect [3] and [4]). Recently a new experiment, called Satellite Test of the Equivalence Principle (STEP), has been proposed [5] as a joint ESA/NASA project. Its aim is to test the (weak) equivalence principle at a fractional accuracy of 10^{-17}, i.e. about six orders of magnitude better than previous tests performed in the twentieth century (notably [6]).

It is well known that the property of universality of free fall was raised by Einstein at the level of a grand principle, now called [7] the Einstein Equivalence Principle, asserting local equivalence between gravitational and inertial forces. With the help of this principle, Einstein succeeded in discovering an entirely new theory of gravity: General Relativity. However, during many years Einstein's theory of gravity stayed somewhat out of contact with the rest of physics, as well as with experiment. This detrimental situation changed in the early sixties, when a favorable situation involving the availability of new technologies (including the Mössbauer effect, radar and laser ranging to solar system bodies, atomic clocks, ...), and the conception of new tests of relativistic gravity [3,8–13], led to an intensive period of research in experimental gravity. From a theoretical point of view, the planning and interpretation of experimental tests was greatly assisted by two different but complementary approaches: on the one hand, the existence of a specific, theoretically well-motivated, one-parameter family of alternative theories of gravity, originally due to Jordan [14] and Fierz [15], and further developed by Brans and Dicke [16]; and on the other hand, the development of a general phenomenological framework, the parametrized post-Newtonian (PPN) formalism [17–20], able to describe with a minimum of theoretical assumptions the many directions in which very generic alternative theories of gravity might differ in their predictions from general relativity. The main conclusion one can draw from all the experimental results about solar-system gravity is that, within the assumptions of the PPN framework (notably the absence of any specific length scale in the gravitational interaction), the limiting regime of weak and quasi-stationary gravitational fields has been fairly completely mapped out at the first post-Newtonian level, i.e. when taking into account fractional corrections of order $(v/c)^2 \sim GM/c^2R$ to a Newtonian description of gravity, and found to agree with general relativity within a fractional accuracy of about 2×10^{-3} [7,21,22].

In spite of the impressive quantitative value of solar system tests, their qualitative value seems relatively limited when one considers that studying the behavior of the gravitational interaction in the combined weak-field-quasi-stationary ("post-Newtonian") limit is somewhat similar to studying the behavior of a function, say $f(x)$, in a small neighborhood of one point, say $x = 0$. Seen from this point of view, the general PPN expansion is analogous to parametrizing, near $x = 0$, the behavior of a general class of functions by means, say, of a parabolic approximation, $f(x) = \alpha + \beta x + \gamma x^2 + O(x^3)$. Clearly such a local parametrization of $f(x)$ is unable to distinguish among functions which approximate each other closely at $x = 0$, but behave very differently in the large. And indeed, the PPN formalism has provided several specific examples of theories, e.g. Rosen's bimetric theory, which approximate general relativity in the post-Newtonian regime while leading to very different predictions in the strong-field and/or rapidly-varying-field regimes [7].

Fortunately, the discovery [23] and continuous observational study of the binary pulsar PSR 1913+16 [24–28] has provided us with a new laboratory for studying relativistic gravity. The distinguishing feature of this laboratory with respect to the solar-system one is that, since the pulsar and its companion are believed to be neutron stars, i.e. objects with more than a solar mass of material compressed within a radius of about 10 km, we have, for the first time, data about a system which contains some strong gravitational-field regions (surface fields $GM/c^2R \sim 0.2$, as compared to $\sim 10^{-6}$ for the Sun). Moreover, the high stability of the pulsar clock has made it possible to monitor the dynamics of its orbital motion down to a precision where extremely small effects, $(v/c)^5$ times smaller than the main gravitational attraction, show up as gravitational radiation damping. At present the coherent recording over sixteen years of pulse arrival times from PSR 1913+16 has provided data which are very well fitted by a phenomenological, i.e. theory-independent, timing model (called BT+) comprising, besides the expected "Keplerian" parameters (notably, the orbital period P_b, the eccentricity e, and the projected semi-major axis of the pulsar orbit $x \equiv a_1 \sin i/c$), three "post-Keplerian" parameters: the secular advance of the periastron, $\dot{\omega}$, a time dilation parameter, γ, and the secular change of the orbital period, $\dot{P}_b$.

Any given relativistic theory of gravity makes a specific prediction for the values of $\dot{\omega}$, γ and $\dot{P}_b$ as functions of the Keplerian parameters and the (a priori unknown) inertial masses, m_1 and m_2, of the pulsar and its companion. In graphical terms, the phenomenological measurement of each post-Keplerian (PK) parameter in the set $\dot{\omega}$,γ and $\dot{P}_b$ defines (when interpreted within the framework of a specific theory of gravity) a curve in the m_1, m_2 plane. It follows that simultaneous measurement of all three PK parameters yields one test of the theory, according to whether the three corresponding curves meet at one point, as they should. As first announced in 1979 [25], and confirmed with ever increasing accuracy as more data were accumulated [26–28], general relativity passes this $\dot{\omega}-\gamma-\dot{P}_b$ test with flying colors when using as the theoretical prediction for $\dot{P}_b$ a formula first obtained heuristically [29], and then derived more rigorously through a study of the general relativistic dynamics of binary systems of strongly self-gravitating bodies [30–33]. Recently, the precision of the $\dot{\omega}-\gamma-\dot{P}_b$ test in PSR 1913+16 data has become so good that it became necessary to correct for the small combined effect of Galactic acceleration and proper motion on the observable orbital period change [34].

Besides providing the first experimental evidence for the existence of gravitational radiation, the $\dot{\omega}-\gamma-\dot{P}_b$ test also represents our first probe of the strong gravitational field regime, and therefore has some important consequences. For example, Rosen's bimetric theory, which has the same post-Newtonian limit as general relativity, fails the test by several orders of magnitude because of the interplay between strong-field and radiative effects [35,7]. (As pointed out in Ref. [36], it also fails the test because of weak-field radiative effects). However, the $\dot{\omega} - \gamma - \dot{P}_b$ test is a mixed test which combines strong–field and radiative effects in an indistinct way, so that one cannot logically conclude, when the test is satisfied, that both the specific strong–field and radiative predictions of general relativity have been independently confirmed. In fact, examples of theoretically well motivated theories have recently been constructed [37] which have the same post–Newtonian limit as general relativity, and can pass the $\dot{\omega} - \gamma - \dot{P}_b$ test without fine tuning, while still differing markedly from Einstein's theory because of the strong self–gravity effects in the pulsar and its companion.

The mixed nature of the $\dot{\omega} - \gamma - \dot{P}_b$ test in PSR 1913+16 raises the following question: Is it possible to extract other tests of relativistic gravity from binary pulsar measurements, specifically tests that probe the quasi–stationary, strong–field aspects of the gravitational interaction? The answer to this question is affirmative, at least in principle, as has been shown by several authors considering different aspects of pulsar data. Immediately after the discovery of PSR 1913+16, it was pointed out [38–40] that a spinning binary pulsar should precess because of relativistic gravitational spin–orbit coupling, and that this effect would show up as a slow change of shape of the electromagnetic pulse as recorded on Earth. Other investigations have shown [41–43, 4] that timing observations of binary pulsars can provide several new tests of strong–field gravity.

Very recently Damour and Taylor [44] have reconsidered the problem and provided a very general framework aimed at exhibiting the maximum theoretical information available, in principle, in binary pulsar data. They considered the information present both in timing data and in pulse–structure data (pulse shape, polarization, ...). Their approach is two–pronged. First, an expanded phenomenological framework, the "parametrized post–Keplerian" (PPK) formalism, allows one to extract the maximum information content from binary pulsar data in a theory–independent way. Then, the analysis of the phenomenological information so extracted by means of a family of alternative theories parametrized by several real parameters helps to elucidate the physical meaning of the raw measurements, and to transform them into explicit quantitative limits on possible strong–field deviations from the correct theory of gravity. The final outcome of their approach is to interpret binary pulsar data as defining "allowed regions" in a multi–dimensional space of possible theories. This allows one to combine data coming from various pulsar systems. Finally, the correct theory of gravity must belong to the intersection (if any) of the various corresponding allowed regions. A convenient family of alternative theories are the tensor–multi–scalar theories studied by Damour and Esposito–Farèse [37], and, in particular, a specific two–parameter class of tensor–bi–scalar theories, denoted $T(\beta', \beta'')$. The latter theories have the same quasi–stationary weak–field limit as General Relativity (so that they satisfy all existing solar–system gravitational tests) but differ in their strong–field, and radiative, predictions when the parameters (β', β'') differ from (0,0). The two parameters β' and β'' play a role in the strong–field regime analogous to the "parametrized post–Newtonian" (PPN) parameters β, γ, ... [17,18,12,13], in the weak–field regime. The methodology advocated in Ref. [44] has been recently applied [45] to real pulsar data coming from three different binary systems: PSR 1913+16, PSR 1855+09 (following [4]), and the newly discovered system PSR 1534+12 [46]. After combining the three independent tests the remaining available theory–space is a rather small strip in the $\beta' - \beta''$ plane. However, since the point (0,0) lies well inside the acceptable region, one can conclude that Einstein's theory has passed several new, deep, and sensitive experimental tests. The most important new fact, compared with previous tests (including the celebrated $\dot{\omega} - \gamma - \dot{P}_b$ test in PSR 1913+16) is that, among these tests several have probed the quasi–stationary strong–field regime of relativistic gravity, without mixing of radiative effects. Moreover, numerical simulations carried out in Ref. [44] provide good reasons for optimism concerning further improvement of these experimental results. In particular, one expects that extended and/or improved observations of the new system PSR 1534+12 should within a few years yield much tighter strong–field tests, including tests of the relativistic spin–orbit coupling.

In the present brief review we have concentrated on existing experimental tests of general relativity. To finish one should mention that several solar–system experiments are presently in development (GPB, POINTS,..., see e.g. Ref. [22]), and that a significant part of the efforts in the field of experimental gravitation is devoted to the construction of detectors of gravitational radiation (notably large interferometric detectors, GEO, LIGO, VIRGO, ..., see e.g. [47] for a review).

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