14. EXPERIMENTAL TESTS OF GRAVITATIONAL THEORY

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Einstein's General Relativity, the current "standard" theory of gravitation, describes gravity as a universal deformation of the Minkowski metric:

$$g_{\mu\nu}(x^\lambda) = \eta_{\mu\nu} + h_{\mu\nu}(x^\lambda) \ , \text{ where } \eta_{\mu\nu} = \mathrm{diag}(-1,+1,+1,+1) \ . \quad (14.1)$$

Alternatively, it can be defined as the unique, consistent, local theory of a massless spin-2 field $h_{\mu\nu}$, whose source must then be the total, conserved energy-momentum tensor [1]. General Relativity is classically defined by two postulates. One postulate states that the Lagrangian density describing the propagation and self-interaction of the gravitational field is

$$\mathcal{L}_{\mathrm{Ein}}[g_{\mu\nu}] = \frac{c^4}{16\pi G_N}\sqrt{g}g^{\mu\nu}R_{\mu\nu}(g) \ , \quad (14.2)$$

$$R_{\mu\nu}(g) = \partial_\alpha \Gamma^\alpha_{\mu\nu} - \partial_\nu \Gamma^\alpha_{\mu\alpha} + \Gamma^\beta_{\alpha\beta}\Gamma^\alpha_{\mu\nu} - \Gamma^\beta_{\nu\alpha}\Gamma^\alpha_{\mu\beta} \ , \quad (14.3)$$

$$\Gamma^\lambda_{\mu\nu} = \tfrac{1}{2} g^{\lambda\sigma}(\partial_\mu g_{\nu\sigma} + \partial_\nu g_{\mu\sigma} - \partial_\sigma g_{\mu\nu}) \ , \quad (14.4)$$

where G_N is Newton's constant, $g = -\det(g_{\mu\nu})$, and $g^{\mu\nu}$ is the matrix inverse of $g_{\mu\nu}$. A second postulate states that $g_{\mu\nu}$ couples universally, and minimally, to all the fields of the Standard Model by replacing everywhere the Minkowski metric $\eta_{\mu\nu}$. Schematically (suppressing matrix indices and labels for the various gauge fields and fermions and for the Higgs doublet),

$$\begin{aligned}\mathcal{L}_{\mathrm{SM}}[\psi, A_\mu, H, g_{\mu\nu}] = & -\tfrac{1}{4}\sum \sqrt{g} g^{\mu\alpha} g^{\nu\beta} F^a_{\mu\nu} F^a_{\alpha\beta} \\ & - \sum \sqrt{g}\, \overline{\psi}\, \gamma^\mu D_\mu \psi \\ & - \tfrac{1}{2}\sqrt{g} g^{\mu\nu} \overline{D_\mu H} D_\nu H - \sqrt{g}\, V(H) \\ & - \sum \lambda \sqrt{g}\, \overline{\psi}\, H \psi \ , \end{aligned} \quad (14.5)$$

where $\gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2g^{\mu\nu}$, and where the covariant derivative D_μ contains, besides the usual gauge field terms, a (spin dependent) gravitational contribution $\Gamma_\mu(x)$ [2]. From the total action $S_{\mathrm{tot}}[g_{\mu\nu}, \psi, A_\mu, H] = c^{-1}\int d^4x(\mathcal{L}_{\mathrm{Ein}} + \mathcal{L}_{\mathrm{SM}})$ follow Einstein's field equations,

$$R_{\mu\nu} - \tfrac{1}{2} R g_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu} \ . \quad (14.6)$$

Here $R = g^{\mu\nu}R_{\mu\nu}$, $T_{\mu\nu} = g_{\mu\alpha}g_{\nu\beta}T^{\alpha\beta}$, and $T^{\mu\nu} = (2/\sqrt{g})\delta\mathcal{L}_{\mathrm{SM}}/\delta g_{\mu\nu}$ is the (symmetric) energy-momentum tensor of the Standard Model matter. The theory is invariant under arbitrary coordinate transformations: $x'^\mu = f^\mu(x^\nu)$. To solve the field equations Eq. (14.6) one needs to fix this coordinate gauge freedom. E.g. the "harmonic gauge" (which is the analogue of the Lorentz gauge, $\partial_\mu A^\mu = 0$, in electromagnetism) corresponds to imposing the condition $\partial_\nu(\sqrt{g}g^{\mu\nu}) = 0$.

In this *Review*, we only consider the classical limit of gravitation (*i.e.* classical matter and classical gravity). Considering quantum matter in a classical gravitational background already poses interesting challenges, notably the possibility that the zero-point fluctuations of the matter fields generate a nonvanishing vacuum energy density ρ_{vac}, corresponding to a term $-\sqrt{g}\ \rho_{\mathrm{vac}}$ in $\mathcal{L}_{\mathrm{SM}}$ [3]. This is equivalent to adding a "cosmological constant" term $+\Lambda\, g_{\mu\nu}$ on the left-hand side of Einstein's equations Eq. (14.6), with $\Lambda = 8\pi G_N\, \rho_{\mathrm{vac}}/c^4$. Cosmological observations set upper bounds (as well as, possibly, lower bounds) on Λ (see "Astrophysical Constants," Sec. 2 of this *Review*) which, when translated in particle physics units, appear suspiciously small: $\rho_{\mathrm{vac}} \lesssim 10^{-46}$ GeV^4. This bound shows that ρ_{vac}, even if it is not strictly zero, has a negligible effect on the tests discussed below. Quantizing the gravitational field itself poses a very difficult challenge because of the perturbative non-renormalizability of Einstein's Lagrangian. Supergravity and superstring theory offer promising avenues toward solving this challenge.

14.1. Experimental tests of the coupling between matter and gravity

The universality of the coupling between $g_{\mu\nu}$ and the Standard Model matter postulated in Eq. (14.5) ("Equivalence Principle") has many observable consequences. First, it predicts that the outcome of a local non-gravitational experiment, referred to local standards, does not depend on where, when, and in which locally inertial frame, the experiment is performed. This means, for instance, that local experiments should neither feel the cosmological evolution of the universe (constancy of the "constants"), nor exhibit preferred directions in spacetime (isotropy of space, local Lorentz invariance). These predictions are consistent with many experiments and observations. The best limit on a possible time variation of the basic coupling constants concerns the fine-structure constant α_{em} and has been obtained by analyzing a natural fission reactor phenomenon which took place at Oklo, Gabon, two billion years ago [4]

$$-6.7 \times 10^{-17}\mathrm{yr}^{-1} < \frac{\dot{\alpha}_{\mathrm{em}}}{\alpha_{\mathrm{em}}} < 5.0 \times 10^{-17}\mathrm{yr}^{-1} \ . \quad (14.7)$$

The highest precision tests of the isotropy of space have been performed by looking to possible quadrupolar shifts of nuclear energy levels [5]. The (null) results can be interpreted as testing the fact that the various pieces in the matter Lagrangian Eq. (14.5) are indeed coupled to one and the same external metric $g_{\mu\nu}$ to the 10^{-27} level.

The universal coupling to $g_{\mu\nu}$ postulated in Eq. (14.5) implies that two (electrically neutral) test bodies dropped at the same location and with the same velocity in an external gravitational field fall in the same way, independently of their masses and compositions. The universality of the acceleration of free fall has been verified at the 10^{-12} level both for laboratory bodies [6],

$$\left(\frac{\Delta a}{a}\right)_{\mathrm{BeCu}} = (-1.9 \pm 2.5) \times 10^{-12} \ , \quad (14.8)$$

and for the gravitational accelerations of the Moon and the Earth toward the Sun [7],

$$\left(\frac{\Delta a}{a}\right)_{\mathrm{MoonEarth}} = (-3.2 \pm 4.6) \times 10^{-13} \ . \quad (14.9)$$

Finally, Eq. (14.5) also implies that two identically constructed clocks located at two different positions in a static external Newtonian potential $U(\boldsymbol{x}) = \sum G_N m/r$ exhibit, when intercompared by means of electromagnetic signals, the (apparent) difference in clock rate,

$$\frac{\tau_1}{\tau_2} = \frac{\nu_2}{\nu_1} = 1 + \frac{1}{c^2}[U(\boldsymbol{x}_1) - U(\boldsymbol{x}_2)] + O\left(\frac{1}{c^4}\right) \ , \quad (14.10)$$

independently of their nature and constitution. This universal gravitational redshift of clock rates has been verified at the 10^{-4} level by comparing a hydrogen-maser clock flying on a rocket up to an altitude $\sim 10{,}000$ km to a similar clock on the ground [8]. For more details and references on experimental gravity see, *e.g.*, Refs. 9 and 10.

14.2. Tests of the dynamics of the gravitational field in the weak field regime

The effect on matter of one-graviton exchange, *i.e.* the interaction Lagrangian obtained when solving Einstein's field equations Eq. (14.6) written in, say, the harmonic gauge at first order in $h_{\mu\nu}$,

$$\Box h_{\mu\nu} = -\frac{16\pi G_N}{c^4}(T_{\mu\nu} - \tfrac{1}{2}T\eta_{\mu\nu}) + O(h^2) + O(hT) \ , \qquad (14.11)$$

reads $-(8\pi G_N/c^4)T^{\mu\nu}\Box^{-1}(T_{\mu\nu} - \frac{1}{2}T\eta_{\mu\nu})$. For a system of N moving point masses, with free Lagrangian $L^{(1)} = \sum_{A=1}^{N} - m_A c^2\sqrt{1 - \boldsymbol{v}_A^2/c^2}$, this interaction, expanded to order v^2/c^2, reads (with $r_{AB} \equiv |\boldsymbol{x}_A - \boldsymbol{x}_B|$, $\boldsymbol{n}_{AB} \equiv (\boldsymbol{x}_A - \boldsymbol{x}_B)/r_{AB}$)

$$\begin{aligned} L^{(2)} =& \frac{1}{2}\sum_{A\neq B}\frac{G_N\, m_A\, m_B}{r_{AB}}\left[1 + \frac{3}{2c^2}(\boldsymbol{v}_A^2 + \boldsymbol{v}_B^2) - \frac{7}{2c^2}(\boldsymbol{v}_A\cdot\boldsymbol{v}_B)\right. \\ &\left. - \frac{1}{2c^2}(\boldsymbol{n}_{AB}\cdot\boldsymbol{v}_A)(\boldsymbol{n}_{AB}\cdot\boldsymbol{v}_B) + O\left(\frac{1}{c^4}\right)\right] \ . \end{aligned} \qquad (14.12)$$

The two-body interactions Eq. (14.12) exhibit v^2/c^2 corrections to Newton's $1/r$ potential induced by spin-2 exchange. Consistency at the "post-Newtonian" level $v^2/c^2 \sim G_N\, m/rc^2$ requires that one also considers the three-body interactions induced by some of the three-graviton vertices and other nonlinearities (terms $O(h^2)$ and $O(hT)$ in Eq. (14.11)),

$$L^{(3)} = -\frac{1}{2}\sum_{B\neq A\neq C}\frac{G_N^2\, m_A\, m_B\, m_C}{r_{AB}\, r_{AC}\, c^2} + O\left(\frac{1}{c^4}\right) \ . \qquad (14.13)$$

All currently performed gravitational experiments in the solar system, including perihelion advances of planetary orbits, the bending and delay of electromagnetic signals passing near the Sun, and very accurate ranging data to the Moon obtained by laser echoes, are compatible with the post-Newtonian results Eqs. (14.11)–(14.13).

Similarly to what is done in discussions of precision electroweak experiments (see Section 10 in this *Review*), it is useful to quantify the significance of precision gravitational experiments by parameterizing plausible deviations from General Relativity. Endowing the spin-2 excitations with a (Pauli-Fierz) mass term is excluded both for phenomenological (discontinuities in observable predictions [11]) and theoretical (no energy lower bound [12]) reasons. Therefore, deviations from Einstein's pure spin-2 theory are defined by adding new, bosonic, ultra light or massless, macroscopically coupled fields. The addition of a vector (spin 1) field necessarily leads to violations of the universality of free fall and is constrained by "fifth force" experiments. See Refs. [6,13] for compilations of constraints. The addition of a scalar (spin 0) field is the most studied type of deviation from General Relativity, being motivated by many attempts to unify gravity with the Standard Model (Kaluza-Klein program, supergravity, string theory). The technically simplest class of tensor-scalar (spin 2 $\oplus$ spin 0) theories consists in adding a massless scalar field φ coupled to the trace of the energy-momentum tensor $T = g_{\mu\nu}T^{\mu\nu}$ [14]. The most general such theory contains an arbitrary function $a(\varphi)$ of the scalar field, and can be defined by the Lagrangian

$$\begin{aligned} \mathcal{L}_{\rm tot}[g_{\mu\nu}, \varphi, \psi, A_\mu, H] =& \frac{c^4}{16\pi G}\sqrt{g}(R(g) - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi) \\ &+ \mathcal{L}_{\rm SM}[\psi, A_\mu, H, \widetilde{g}_{\mu\nu}] \ , \end{aligned} \qquad (14.14)$$

where G is a "bare" Newton constant, and where the Standard Model matter is coupled not to the "Einstein" (pure spin-2) metric $g_{\mu\nu}$, but to the conformally related ("Jordan-Fierz") metric $\widetilde{g}_{\mu\nu} = \exp(2a(\varphi))g_{\mu\nu}$. The scalar field equation $\Box_g\varphi = -(4\pi G/c^4)\alpha(\varphi)T$ displays $\alpha(\varphi) \equiv \partial a(\varphi)/\partial\varphi$ as the basic (field-dependent) coupling between φ and matter [15]. The one-parameter Jordan-Fierz-Brans-Dicke theory [14] is the special case $a(\varphi) = \alpha_0\varphi$ leading to a field-independent coupling $\alpha(\varphi) = \alpha_0$.

In the weak field, slow motion, limit appropriate to describing gravitational experiments in the solar system, the addition of φ modifies Einstein's predictions only through the appearance of two "post-Einstein" dimensionless parameters: $\overline{\gamma} = -2\alpha_0^2/(1+\alpha_0^2)$ and $\overline{\beta} = +\frac{1}{2}\beta_0\alpha_0^2/(1+\alpha_0^2)^2$, where $\alpha_0 \equiv \alpha(\varphi_0)$, $\beta_0 \equiv \partial\alpha(\varphi_0)/\partial\varphi_0$, φ_0 denoting the vacuum expectation value of φ. These parameters show up also naturally (in the form $\gamma_{\rm PPN} = 1 + \overline{\gamma}$, $\beta_{\rm PPN} = 1 + \overline{\beta}$) in phenomenological discussions of possible deviations from General Relativity [16,9]. The parameter $\overline{\gamma}$ measures the admixture of spin 0 to Einstein's graviton, and contributes an extra term $+\overline{\gamma}(\boldsymbol{v}_A - \boldsymbol{v}_B)^2/c^2$ in the square brackets of the two-body Lagrangian Eq. (14.12). The parameter $\overline{\beta}$ modifies the three-body interaction Eq. (14.13) by a factor $1 + 2\overline{\beta}$. Moreover, the combination $\eta \equiv 4\overline{\beta} - \overline{\gamma}$ parameterizes the lowest order effect of the self-gravity of orbiting masses by modifying the Newtonian interaction energy terms in Eq. (14.12) into $G_{AB}m_Am_B/r_{AB}$, with a body-dependent gravitational "constant" $G_{AB} = G_N[1 + \eta(E_A^{\rm grav}/m_Ac^2 + E_B^{\rm grav}/m_Bc^2) + O(1/c^4)]$, where $G_N = G\exp[2a(\varphi_0)](1+\alpha_0^2)$ and where $E_A^{\rm grav}$ denotes the gravitational binding energy of body A.

The best current limits on the post-Einstein parameters $\overline{\gamma}$ and $\overline{\beta}$ are (at the 68% confidence level): (i) $-3.8\times10^{-4} < \overline{\gamma} < 2.6\times10^{-4}$ deduced from Very Long Baseline Interferometry (VLBI) measurements of the deflection of radio waves by the Sun [17], and (ii) $4\overline{\beta} - \overline{\gamma} = -0.0007 \pm 0.0010$ [7] from Lunar Laser Ranging measurements of a possible polarization of the Moon toward the Sun [18]. More stringent limits on $\overline{\gamma}$ are obtained in models (*e.g.*, string-inspired ones [19]) where scalar couplings violate the Equivalence Principle.

14.3. Tests of the dynamics of the gravitational field in the radiative and/or strong field regimes

The discovery of pulsars (*i.e.* rotating neutron stars emitting a beam of radio noise) in gravitationally bound orbits [20,21] has opened up an entirely new testing ground for relativistic gravity, giving us an experimental handle on the regime of radiative and/or strong gravitational fields. In these systems, the finite velocity of propagation of the gravitational interaction between the pulsar and its companion generates damping-like terms at order $(v/c)^5$ in the equations of motion [22]. These damping forces are the local counterparts of the gravitational radiation emitted at infinity by the system ("gravitational radiation reaction"). They cause the binary orbit to shrink and its orbital period P_b to decrease. The remarkable stability of the pulsar clock has allowed Taylor and collaborators to measure the corresponding very small orbital period decay $\dot{P}_b \equiv dP_b/dt \sim (v/c)^5 \sim 10^{-12}$ [21,23], thereby giving us a direct experimental confirmation of the propagation properties of the gravitational field. In addition, the surface gravitational potential of a neutron star $h_{00}(R) \simeq 2Gm/c^2R \simeq 0.4$ being a factor $\sim 10^8$ higher than the surface potential of the Earth, and a mere factor 2.5 below the black hole limit ($h_{00} = 1$), pulsar data are sensitive probes of the strong-gravitational-field regime.

Binary pulsar timing data record the times of arrival of successive electromagnetic pulses emitted by a pulsar orbiting around the center of mass of a binary system. After correcting for the Earth motion around the Sun and for the dispersion due to propagation in the interstellar plasma, the time of arrival of the Nth pulse t_N can be described by a generic, parameterized "timing formula [24]" whose functional form is common to the whole class of tensor-scalar gravitation theories:

$$t_N - t_0 = F[T_N(\nu_p, \dot{\nu}_p, \ddot{\nu}_p)\,;\, \{p^K\}\,;\, \{p^{PK}\}] \ . \qquad (14.15)$$

Here, T_N is the pulsar proper time corresponding to the Nth turn given by $N/2\pi = \nu_pT_N + \frac{1}{2}\dot{\nu}_pT_N^2 + \frac{1}{6}\ddot{\nu}_pT_N^3$ (with $\nu_p \equiv 1/P_p$ the spin frequency of the pulsar, etc.), $\{p^K\} = \{P_b, T_0, e, \omega_0, x\}$ is the set of "Keplerian" parameters (notably, orbital period P_b, eccentricity e and projected semi-major axis $x = a\sin i/c$), and $\{p^{PK}\} = \{k, \gamma_{\rm timing}, \dot{P}_b, r, s, \delta_\theta, \dot{e}, \dot{x}\}$ denotes the set of (separately measurable) "post-Keplerian" parameters. Most important among these are: the fractional periastron advance per orbit $k \equiv \dot{\omega}P_b/2\pi$, a dimensionful time-dilation parameter $\gamma_{\rm timing}$, the orbital period derivative $\dot{P}_b$, and the "range" and "shape" parameters of the gravitational time delay caused by the companion, r and s.

Without assuming any specific theory of gravity, one can phenomenologically analyze the data from any binary pulsar by least-squares fitting the observed sequence of pulse arrival times to the timing formula Eq. (14.15). This fit yields the "measured" values of the parameters $\{\nu_p, \dot{\nu}_p, \ddot{\nu}_p\}$, $\{p^K\}$, $\{p^{PK}\}$. Now, each specific relativistic theory of gravity predicts that, for instance, k, $\gamma_{\rm timing}$, $\dot{P}_b$, r and s (to quote parameters that have been successfully measured from some binary pulsar data) are some theory-dependent functions of the Keplerian parameters and of the (unknown) masses m_1, m_2 of the pulsar and its companion. For instance, in General Relativity, one finds (with $M \equiv m_1 + m_2$, $n \equiv 2\pi/P_b$)

$$\begin{aligned}
k^{\rm GR}(m_1, m_2) =& 3(1-e^2)^{-1}(G_N M n/c^3)^{2/3} \ , \\
\gamma^{\rm GR}_{\rm timing}(m_1, m_2) =& e n^{-1}(G_N M n/c^3)^{2/3} m_2(m_1 + 2m_2)/M^2 \ , \\
\dot{P}^{\rm GR}_b(m_1, m_2) =& -(192\pi/5)(1-e^2)^{-7/2}\left(1 + \tfrac{73}{24}e^2 + \tfrac{37}{96}e^4\right) \\
& \times (G_N M n/c^3)^{5/3} m_1 m_2/M^2 \ , \\
r(m_1, m_2) =& G_N m_2/c^3 \ , \\
s(m_1, m_2) =& n x (G_N M n/c^3)^{-1/3} M/m_2 \ . \qquad (14.16)
\end{aligned}$$

In tensor-scalar theories, each of the functions $k^{\rm theory}(m_1, m_2)$, $\gamma^{\rm theory}_{\rm timing}(m_1, m_2)$, $\dot{P}^{\rm theory}_b(m_1, m_2)$, etc is modified by quasi-static strong field effects (associated with the self-gravities of the pulsar and its companion), while the particular function $\dot{P}^{\rm theory}_b(m_1, m_2)$ is further modified by radiative effects (associated with the spin 0 propagator) [15,25].

Let us summarize the current experimental situation. In the first discovered binary pulsar PSR1913 + 16 [20,21], it has been possible to measure with accuracy the three post-Keplerian parameters k, $\gamma_{\rm timing}$ and $\dot{P}_b$. The three equations $k^{\rm measured} = k^{\rm theory}(m_1, m_2)$, $\gamma^{\rm measured}_{\rm timing} = \gamma^{\rm theory}_{\rm timing}(m_1, m_2)$, $\dot{P}^{\rm measured}_b = \dot{P}^{\rm theory}_b(m_1, m_2)$ determine, for each given theory, three curves in the two-dimensional mass plane. This yields one (combined radiative/strong-field) test of the specified theory, according to whether the three curves meet at one point, as they should. After subtracting a small ($\sim 10^{-14}$ level in $\dot{P}^{\rm obs}_b = (-2.422 \pm 0.006) \times 10^{-12}$), but significant, Newtonian perturbing effect caused by the Galaxy [26], one finds that General Relativity passes this $(k - \gamma_{\rm timing} - \dot{P}_b)_{1913+16}$ test with complete success at the 10^{-3} level [21,23]

$$\begin{aligned}
\left[\frac{\dot{P}^{\rm obs}_b - \dot{P}^{\rm galactic}_b}{\dot{P}^{\rm GR}_b[k^{\rm obs}, \gamma^{\rm obs}_{\rm timing}]}\right]_{1913+16} =& 1.0032 \pm 0.0023({\rm obs}) \pm 0.0026({\rm galactic}) \\
=& 1.0032 \pm 0.0035 \ . \qquad (14.17)
\end{aligned}$$

Here $\dot{P}^{\rm GR}_b[k^{\rm obs}, \gamma^{\rm obs}_{\rm timing}]$ is the result of inserting in $\dot{P}^{\rm GR}_b(m_1, m_2)$ the values of the masses predicted by the two equations $k^{\rm obs} = k^{\rm GR}(m_1, m_2)$, $\gamma^{\rm obs}_{\rm timing} = \gamma^{\rm GR}_{\rm timing}(m_1, m_2)$. This experimental evidence for the reality of gravitational radiation damping forces at the 0.3% level is illustrated in Fig. 14.1, which shows actual orbital phase data (after subtraction of a linear drift).

The discovery of the binary pulsar PSR1534 + 12 [27] has allowed one to measure the four post-Keplerian parameters k, $\gamma_{\rm timing}$, r and s, and thereby to obtain two (four observables minus two masses) tests of strong field gravity, without mixing of radiative effects [28]. General Relativity passes these tests within the measurement accuracy [28,21]. The most precise of these new, pure, strong-field tests is the one obtained by combining the measurements of k, γ, and s. Using the most recent data [29], one finds agreement at the 1% level:

$$\left[\frac{s^{\rm obs}}{s^{\rm GR}[k^{\rm obs}, \gamma^{\rm obs}_{\rm timing}]}\right]_{1534+12} = 1.007 \pm 0.008 \ . \qquad (14.18)$$

It has also been possible to measure the orbital period change of PSR1534 + 12. General Relativity passes the corresponding $(k - \gamma_{\rm timing} - \dot{P}_b)_{1534+12}$ test with success at the 15% level [29].

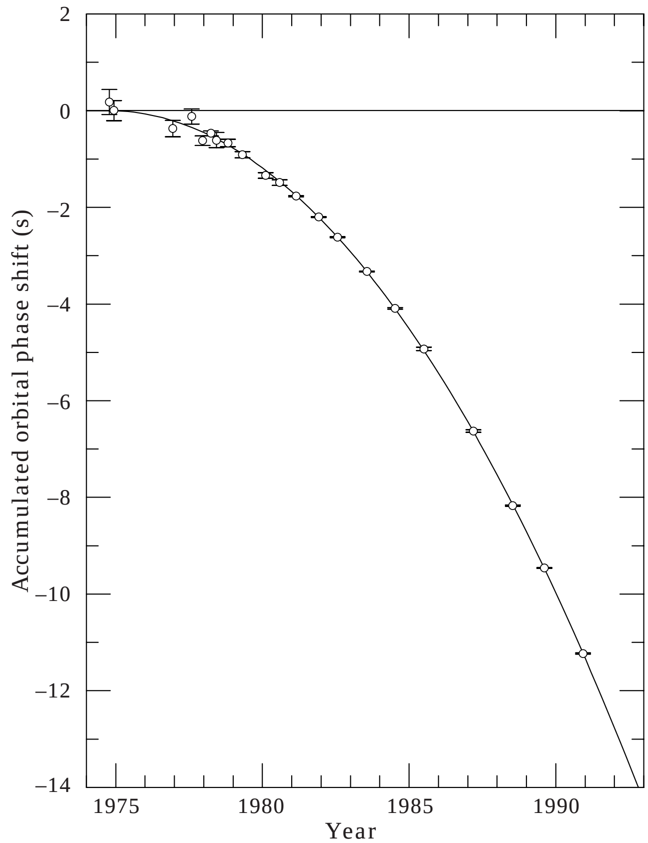

Figure 14.1: Accumulated shift of the times of periastron passage in the PSR 1913+16 system, relative to an assumed orbit with a constant period. The parabolic curve represents the general relativistic prediction, modified by Galactic effects, for orbital period decay from gravitational radiation damping forces. (Figure obtained with permission from Ref. 21.)

Several other binary pulsar systems, of a nonsymmetric type (nearly circular systems made of a neutron star and a white dwarf), can also be used to test relativistic gravity [30,31]. The constraints on tensor-scalar theories provided by three binary-pulsar "experiments" have been analyzed in [25] and shown to exclude a large portion of the parameter space allowed by solar-system tests. Recently, measurements of the pulse shape of PSR1913 + 16 [32] have detected a time variation of the pulse shape compatible with the prediction [33] that the general relativistic spin-orbit coupling should cause a secular change in the orientation of the pulsar beam with respect to the line of sight ("geodetic precession").

The tests considered above have examined the gravitational interaction on scales between a few centimeters and a few astronomical units. Millimeter scale tests of Newtonian gravity have been reported in Ref. 34. On the other hand, the general relativistic action on light and matter of an external gravitational field on a length scale ~ 100 kpc has been verified to $\sim 30\%$ in some gravitational lensing systems (see, *e.g.*, Ref. 35). Some tests on cosmological scales are also available. In particular, Big Bang Nucleosynthesis (see Section 15 of this *Review*) has been used to set significant constraints on the variability of the gravitational "constant" [36].

14.4. Conclusions

All present experimental tests are compatible with the predictions of the current "standard" theory of gravitation: Einstein's General Relativity. The universality of the coupling between matter and gravity (Equivalence Principle) has been verified at the 10^{-12} level. Solar system experiments have tested the weak-field predictions of Einstein's theory at the 10^{-3} level. The propagation properties of relativistic gravity, as well as several of its strong-field aspects, have been verified at the 10^{-3} level in binary pulsar experiments. Several important new developments in experimental gravitation are expected in the near future. The approved NASA Gravity Probe B mission (a space gyroscope experiment; due for launch within the next two years) will directly measure the gravitational spin-orbit and spin-spin couplings, thereby measuring the weak-field post-Einstein parameter $\overline{\gamma}$ to the 10^{-5} level. The planned NASA-ESA MiniSTEP mission (a satellite test of the Equivalence Principle) should test the universality of acceleration of free fall down to the 10^{-18} level (an improvement by six orders of magnitude). Laboratory experiments (motivated by recent theoretical ideas [37]) plan to test possible deviations from standard Newtonian gravity on sub-millimeter distance scales. Finally, the various kilometer-size laser interferometers under construction (notably LIGO in the USA and VIRGO in Europe) should, soon after 2002, directly detect gravitational waves arriving on Earth. As the sources of these waves are expected to be extremely relativistic objects with strong internal gravitational fields (*e.g.*, coalescing binary black holes), their detection will allow one to experimentally probe gravity in highly dynamical circumstances.

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