Pulsars as probes of gravity and fundamental physics

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Radio-loud neutron stars known as pulsars allow a wide range of experimental tests for fundamental physics, ranging from the study of super-dense matter to tests of general relativity and its alternatives. As a result, pulsars provide strong-field tests of gravity, they allow for the direct detection of gravitational waves in a ‘pulsar timing array’, and they promise the future study of black hole properties. This contribution gives an overview of the on-going experiments and recent results.

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1. Introduction

With the direct detection of gravitational waves using Earth-bound detectors, an enormous milestone in testing gravity has been achieved. Even though we had indisputable evidence that gravitational waves exist from precision pulsar observations, a direct detection on Earth is important to open up the new field of gravitational wave astronomy. But even in light of this massive achievement that we can all celebrate exactly 100 years after Einstein presented his general theory of relativity (GR), there is still a role of radio astronomy and pulsar observations in our quest to understand gravity and fundamental physics. This review will highlight some of the areas where radio pulsar observations continue to be crucial. It will also describe how “Pulsar Timing Array” (PTA) experiments will join the Earth-bound experiments to detect gravitational waves directly and how they complement each other. Finally, after the wonderful evidence for the existence of stellar-mass black holes presented by the LIGO collaboration, we present methods how pulsar observations can be combined with imaging observations to study the properties of the supermassive black hole in the centre of the Galaxy in great detail.

1.1. Fundamental physics tested using radio astronomy

Radio photons are the least energetic ones used by astronomers. Yet, their origin is often associated with highly energetic processes, coming frequently from areas of extreme conditions involving high energies, high gravitational or magnetic fields. They are also relatively easy to detect, to multiply and to interfere with each other. They can carry polarisation information that can easily be extracted, allowing us to probe for instance the imprint of intervening magnetic fields, giving access to plasma physics or geometric information. And, even though it may take large telescope
structures to detect the weak radio signals, and even though detectors may need to be spaced across large distances (and perhaps even into space), in order to get high spatial resolution images, the radio window of the electromagnetic spectrum is a doorway to an effective laboratory for fundamental physics: Testing for a possible a variation of fundamental constants across cosmic time is possible with the method of molecular spectroscopy, studying emission that originates from distant quasars. The Cosmic Microwave Background (CMB) is a signal from the early Universe that is redshifted so much, that it now appears in the radio. Observations of water masers emitting powerful coherent radio emission allow the establishment of an accurate distance ladder to measure the local expansion of the Universe. These and some other examples are summarised in Table 1. Despite all these examples, overall there is arguably no other type of object where astronomy overlaps so widely with fundamental physics as in the case of radio pulsars.

2. A Simple and Clean Experiment: Pulsars and their Timing

Pulsars are extremely useful tools for the study of many aspects of fundamental physics. This is for several reasons: firstly, as neutron stars they are very compact, strongly-selfgravitating bodies. With masses of up to $2M_\odot$ (see Section 6) concentrated on a radius of about 10-12 km, or so, they represent the densest observable matter in the Universe. Understanding the properties of matter under extreme pressure, i.e. the Equation-of-State, requires the study of neutron star material. Secondly, pulsars rotate with spin frequencies up to $\sim 700$ Hz, storing an amount of rotational energy, that makes especially the fast spinning “millisecond pulsars” massive stable flywheels in space. Thirdly, pulsars emit a collimated beam of coherent radio light along their magnetic axis, making them cosmic lighthouses, the stable rotation of which can be studied by “timing” the arrival times here on Earth. In essence, physicists have been gifted with a natural precise clock that is attached to a strongly self-gravitating body. Especially if the pulsar has another compact binary companion, it can be used to study the effects on the surrounding spacetime, making it an ideal tool to study gravity under strong-field conditions.

2.1. The method

In pulsar timing, the arrival time of the pulse of a pulsar is measured and recorded on Earth. By a comparison of the times measured on Earth, transferred to the emission time in the pulsar frame, each single rotation of the pulsar can be tracked and effects influencing the signal during its propagation through spacetime (at the pulsar and the solar system) and the interstellar medium can be studied with great precision. The precision is achieved by describing the pulsar rotation phase-coherently (i.e. coherent in rotational phase, so that not a single rotation is missed). Consequently, all parameters describing the pulsar (spin-down, astrometry, binary motion, relativistic effects) included in the “timing model” can usually be measured with a
Table 1. Selected aspects of fundamental physics studied with radio astronomical techniques. Note that some solar system tests have better numerical precision but are derived in weak gravitational field of the Solar System. In contrast, binary pulsar limits may sometimes be less constraining in precision, but they are derived for strongly self-gravitating bodies where deviations are generally expected to be larger. References are given for more information or further reading. For a general review see Will (2014), and for pulsar-related limits see Wex (2014).

| Tested phenomena | Method | Radio astronomy | Ref. |
|-----------------|--------|-----------------|------|
| Variation of fundamental constants: | | |
| Fine structure constant $\left(\frac{e^2}{\hbar c}\right)$ | Clock comparison, radio active decays, limit depending on redshift, $< \sim 10^{-16}$ yr$^{-1}$ | Quasar spectra, $< 10^{-16}$ yr$^{-1}$ | 5 |
| e-p mass ratio | Clock comparison | Quasar spectra, $< 3 \times 10^{-15}$ yr$^{-1}$ | 6, 7 |
| Gravitational constant, $G/G$ | Lunar Ranging (LLR), $\left(\frac{0.7 \pm 3.8}{10^{-13}}\right)$ yr$^{-1}$ | Binary pulsars, $\left(\frac{-0.6 \pm 3.2}{10^{-12}}\right)$ yr$^{-1}$ | 8, 9, 10 |

| Universality of free fall: | | |
| LLR, Nordtvedt parm. $|\eta| = (4.4 \pm 4.5) \times 10^{-4}$ | Binary Pulsars, $\Delta < 5.6 \times 10^{-3}$ | 5, 11, 10 |

| Universal preferred frame for gravity: | see Table 2 |

| PPN parameters and related phenomena: | see Table 2 |

| Gravitational wave properties: | Binary pulsars | 10 |
| Verification of GRs quadrupole formula | Double Pulsar, $< 10^{-3}$ | 12 |
| Constraints on dipolar radiation | PSR-WD systems, $(\alpha_A - \alpha_B)^2 < 4 \times 10^{-16}$ | 9, 13 |

| Geodetic precession | Gravity Probe B, 0.3% | PSR B1913+16: Double Pulsar, 13%; PSR B1534+12, 17% | 14, 15, 16 |

| Equation-of-State | e.g. thermal emission from X-ray binaries | fast spinning pulsars; massive neutron stars | 17, 18, 19, 13 |

| Cosmology | e.g. Supernova distances | Cosmic Microwave Background | this conference |

high precision that continues to improve with time. Details of the procedure can be found, for instance, in Ref. 20.

2.2. The laboratories

While isolated pulsars also provide insight in a number of aspects of gravity (e.g. preferred frame and position effects), the majority of results are obtained with binary pulsars. The nature of companions represents all possible outcomes: main-sequence stars, evolved stars, planets, white dwarfs, other neutron stars and pulsars. The
only exception is a current lack of pulsar-black hole systems. These systems should exist, but they may be rare, and it is still likely that selection effects in finding compact and fast binary pulsars prevent the successful discovery so far. Most likely, it is a combination of both, and it requires a complete census of the Galactic pulsar population (as planned with the Square Kilometre Array (SKA)\textsuperscript{22,23}) to find and calibrate the population synthesis calculations. So far, the majority of binary systems comprises pulsar-white dwarf systems, but the number of known so called “double neutron star” systems (DNSs) is increasing steadily (see e.g. contribution by Freire in this conference). The results are nevertheless impressive, not only in variety of measurements, but especially when it comes to precision of the measurements (Tab. 2).

Table 2. Examples of precision measurements using pulsar timing as a variation demonstration what is possible today. The digit in bracket indicates the uncertainty in the last digit of each value. References are cited in the last column.

| Masses:                  | \(m_1 = 1.4398(2)\,M_\odot\) | 3  |
|-------------------------|-------------------------------|----|
| Masses of neutron stars:| \(m_2 = 1.3886(2)\,M_\odot\) | 3  |
| Mass of WD companion:   | 0.207(2)\,M_\odot            | 24 |
| Mass of millisecond pulsar: | 1.67(2)\,M_\odot            | 25 |
| Main sequence star companion: | 1.029(8)\,M_\odot         | 25 |
| Mass of Jupiter and moons: | 9.547921(2) \times 10^{-4}\,M_\odot | 26 |
| Spin parameters:        |                               |    |
| Period:                 | 5.757451924362137(2) ms      | 27 |
| Orbital parameters:     |                               |    |
| Period:                 | 0.102251562479(8) day         | 12 |
| Eccentricity:           | 3.5(1.1) \times 10^{-7}      | 9  |
| Astrometry:             |                               |    |
| Distance:               | 157(1) pc                     | 27 |
| Proper motion:          | 140.915(1) mas yr\(^{-1}\)    | 27 |
| Tests of general relativity: | 4.226598(5) deg yr\(^{-1}\) | 3  |
| Periastron advance:     | 7.152(8) mm/day               | 12 |
| Shrinkage due to GW emission: | 1.0000(5) mm/day       | 12 |
| GR validity (obs/exp):  | \(-0.6(1.6) \times 10^{-12}\) yr\(^{-1}\) | 9  |

3. Pulsars as Gravitational Wave Detectors

The idea of using pulsars not only as sources of GWs in binary systems, but to also use them as GW detectors is 40 years old. The idea is simple, but as for LIGO, the realisation is a challenge - but also one that should be mastered eventually. If a low-frequency GW distorts the local space-time near Earth, it should be visible as an red noise signal in the pulsar timing residuals. In order to recognise it as an astrophysical signal, we need to distinguish it from other sources of noise. This
is possible since distortions of the local space-time affect all timed pulsars, not in the same way, but as described by the polarisation characteristics of the GW. For an (expected) quadrupolar polarisation, pulsars in the same or opposite direction on the sky should show a positive correlation in their arrival time (i.e. the pulses arrive simultaneously too early or too late), while pulsars at right angles on the sky, should be anti-correlated. The exact relationship for a stochastic background of GWs is expressed in the “Helling-and-Downs” curve (for quadrupolar polarisation, for other polarisation modes see below) as first computed in Ref. 28.

In other words, it requires an ensemble of pulsars to make a reliable detection. The frequency range that this “Pulsar Timing Array” (PTA) is sensitive to depends both the cadence of the observations and the length of the data set. With a typical cadence of days to weeks, and a time-baseline of nearly 20 years or more (see e.g. the recent results of the European Pulsar Timing Array, EPTA, with data sets spanning up to 18 years, this corresponds to a frequency range from $(18 \text{ years})^{-1} = 1.8 \text{nHz}$ to $(1 \text{ week})^{-1} = 1600 \text{ nHz}$. (NB: The “high” frequency end is less probed currently, as high cadence observations were started only relatively recently for most sources). The resulting shape of the sensitivity curve plotted into a diagram of characteristic strain vs. GW frequency is wedge-like, with the sharp low-frequency end given by the data set length. At the frequency of $1 \text{ year}^{-1}$, the PTA are insensitive, as any GW signal would be absorbed for a fit to the astrometric parameters, measurable due to the Earth movement about the Sun.

3.1. Status of the PTA efforts

There are three major PTA experiments in the world at the moment. There is the European Pulsar Timing Array (EPTA)

30 the North American Gravitational Wave Observatory (NANOGrav)

31 and the Parkes Pulsar Timing Array (PPTA). All of these experiments conduct regular multi-frequency timing observations of 20 to 40 millisecond pulsars. The aim of these efforts is to detect GWs in the nHz-regime. The strongest signal that can be expected is the superposition of signals emitted by super-massive black hole binaries (SMBHBs). In the simplest form, one would expect a power-law signal with a spectral index of $f^{-2/3}$ and a characteristic strain amplitude at a frequency of $(1 \text{ year})^{-1}$ of about $10^{-15}$. In reality the shape of the spectrum depends on astrophysical processes during galaxy mergers (for a review see, for instance, Ref. 33), demonstrating that an eventual detection of the signal is not only important for GW research, but also for studies of the physics of galaxy formation and mergers. So far, only upper limits on the stochastic signal could be obtained. With similar and complementary capabilities the results of all PTA are comparable, producing limits that are all comparable within factors 2 to 3 (see Refs. 34, 35, 36). In order to increase the sensitivity and frequency coverage of the PTAs the three experiments also pool their data within the International Pulsar Timing Array (IPTA). It can be expected that the current results will improve considerably in the future. In particular the addition of the most recent and hence
most accurate data will go a long way towards a detection that would complement the Earth-bound (and later space-bound) window with very low nHz-frequencies. In particular the addition of results from the Large European Array for Pulsars (LEAP) promise to boost the overall EPTA and IPTA capabilities. See also the contribution by Perrodin and others for more details.

### 3.2. PTA science beyond detection

Like in the case of LIGO, a PTA detection of GWs would only be the first step towards physics and astrophysics enabled by GW astronomy. Understanding the astrophysics of SMBBH mergers is only one obvious topic to be better understood by PTA signals. A high-precision measurement of the Hellings-Downs curve enabled by the SKA, also allows to measure or constrain the properties of gravitational waves. It is easy to see that the shape of the curve is affected by deviations from a quadrupolar nature of the GWs, or a deviation of the graviton spin from 2. Indeed, in alternative theories, up to six polarisation modes are possible, that can be explored and constrained by very sensitive PTA observations. Similarly, but perhaps less obvious, is the fact that a non-zero mass of the graviton would introduce a cut-off frequency beyond which GW propagation in the Universe is not possible. This also modifies the Hellings-Downs curve and should be detectable in future SKA observations.

### 4. Constraining PPN Parameters

Tests in the weak-field limit, as for instance conducted in the solar system, can be performed within the framework of the Parameterised Post-Newtonian (PPN) formalism. Here, a particular effect can be associated with a particular PPN parameter, which assumes a certain value in GR, but may have different values in alternative theories of gravity. Table 3, adapted from a similar table in Ref. 43, summarises the PPN parameters and their values in which a general theory of gravity can differ from GR at 1PN level. While they are used to describe theories in the limit in which the gravitational field is weak and generated by objects moving slowly compared to the speed of light, it is possible to write down “strong-field equivalents”, which can then be tested with pulsars. Again, Table 3 summarised the current best limits, where indeed the majority is now constrained by pulsars (see Ref. 10) for details).

### 5. Binary Pulsars

Binary pulsars in compact, ideally eccentric, orbits, may show a number of relativistic effects that influence the pulse arrival times in a variety of ways. They manifest themselves as deviations from the classical Keplerian motion of these “relativistic binaries”, and they can be described by theory-independent corrections to the binary motion, so called “Post-Keplerian (PK) Parameters” as introduced
Table 3. Best limits for the parameters in the PPN formalism. Note that 6 of the 9 independent PPN parameters are best constrained by radio astronomical techniques. Especially, five of them are derived from pulsar observations. Adapted from Will (2014) but see also Wex (2014) for details.

| Par. Meaning | Method | Limit | Remark/Ref. |
|--------------|--------|-------|-------------|
| $\gamma - 1$ How much space-curvature produced by unit rest mass? | time delay | $2.3 \times 10^{-5}$ | Cassini tracking/5 |
| | light deflection | $2 \times 10^{-4}$ | VLBI/5 |
| $\beta - 1$ How much “non-linearity” in the superposition law for gravity? | perihelion shift | $8 \times 10^{-5}$ | using $J_{2\odot} = (2.2 \pm 0.1) \times 10^{-7}$/5 |
| | Nordtvedt effect | $2.3 \times 10^{-4}$ | $\eta_N = 4\beta - \gamma - 3$ assumed |
| $\xi$ Preferred-location effects? | spin precession | $4 \times 10^{-9}$ | Isolated MSPs/44 |
| $\alpha_1$ Preferred-frame effects? | orbital polarisation | $4 \times 10^{-5}$ | PSR-WD, PSR J1738+0333/45 |
| | spin precession | $2 \times 10^{-9}$ | Using isolated MSPs/46 |
| $\alpha_3$ orbital polarisation | $5.5 \times 10^{-20}$ | Using ensemble of MSPs/47 |
| $\zeta_1$ Violation of conservation of total momentum? | Combining PPN bounds | $2 \times 10^{-2}$ | 5 |
| $\zeta_2$ binary acceleration | $4 \times 10^{-5}$ | Using $\ddot{P}$ for PSR B1913+16/5 |
| $\zeta_3$ Newton’s 3rd law | $10^{-8}$ | lunar acceleration/5 |
| $\zeta_4$ not independent | $6\zeta_4 = 3\sigma_3 + 2\zeta_1\zeta_5$ |

by Refs. 48, 49. The PK parameters depend on the well-measured Keplerian parameters and the a priori unknown masses of the binary components, whereas the functional dependence on them is determined by a given theory of gravity. With the measurement of two PK parameters, the two masses can be determined, assuming the particular theory. The theory can be tested for consistency if one or more additional PK parameters can be measured. The measured value can be compared with the one determined using the functional dependence and the calculated masses. If the values disagree, the chosen theory is falsified.

5.1. The Hulse-Taylor pulsar

The first system, where such a described test was possible, was the first binary pulsar discovered by Hulse and Taylor, PSR B1913+16 (Ref. 2). The system allowed the measurement of three PK parameters.

The easiest to be measured for binary pulsars (unless the orbit is circular) is the
advance of periastron, which in GR is given by

\[ \dot{\omega} = 3T^{2/3}{\left(\frac{P_b}{2\pi}\right)}^{5/3} \frac{1}{1-e^2} (m_p + m_c)^{2/3}. \]  

(1)

Here, \( T_\odot = GM_\odot/c^3 = 4.925490947\mu s \) is a constant, \( P_b \) the orbital period, \( e \) the eccentricity, and \( m_p \) and \( m_c \) the masses of the pulsar and its companion. See Ref. 20 for further details.

The second parameter describes the effects of time dilation as the pulsar moves in its elliptical orbit at varying distances from the companion and with varying speeds. In GR, the observed amplitude of the integrated effect is related to the Keplerian parameters and the masses as

\[ \gamma_E = T^{2/3}{\left(\frac{P_b}{2\pi}\right)}^{1/3} \frac{1}{(m_p + 2m_c)} \frac{m_c(m_p + 2m_c)}{(m_p + m_c)^{1/3}}. \]  

(2)

By measuring \( \dot{\omega} \) and \( \gamma_E \), one can determine the masses assuming GR, \( m_p = 1.4398 \pm 0.0002 M_\odot \) and \( m_c = 1.3886 \pm 0.0002 M_\odot \) (Ref. 3).

With time, it was possible to measure the shrinkage of the orbit due to the emission of gravitational waves, which manifests itself in a shift of periastron time to earlier times. This allows to determine the change in orbital period, which in GR depends on

\[ \dot{P}_b = -\frac{192}{5} T^{5/3}{\left(\frac{P_b}{2\pi}\right)}^{5/3} \frac{1}{(1-e^2)^{7/2}} \frac{m_pm_c}{(m_p + m_c)^{1/3}}. \]  

(3)

The predicted value using this relationship agrees with the observed value, however, only if a correction for a relative acceleration between the pulsar and the solar system barycentre is taken into account. As the pulsar is located about 7-8 kpc away from Earth, it experiences a different acceleration in the Galactic gravitational potential than the solar system (see e.g. Ref. 20). The precision of our knowledge to correct for this effect eventually limits our ability to compare the GR prediction to the observed value. Nevertheless, the agreement of observations and prediction, today within a 0.2% (systematic) uncertainty (Ref. 3), represented the first evidence for the existence of gravitational waves.

5.2. The Double Pulsar

Today we know many more binary pulsars where we can detect gravitational wave emission. In the particular case of the Double Pulsar, the measurement uncertainties are not only more precise, but also the systematic uncertainties are much smaller, as the system is much more nearby. However, what makes the system particularly unique is the fact that the system consists of two active radio pulsars\(^a\)

\(^a\)As we describe later, one of them is temporarily not visible due to the effects of relativistic spin precession.
One pulsar is mildly recycled with a period of 23 ms (named “A”), while the other pulsar is young with a period of 2.8 s (named “B”). Both orbit the common centre of mass in only 147-min with orbital velocities of 1 Million km per hour. Being also mildly eccentric ($e = 0.09$), the system is an ideal laboratory to study gravitational physics and fundamental physics in general. A detailed account of the exploitation for gravitational physics has been given, for instance, by Refs. 4, 50, 51.

An update on those results is in preparation (Ref. 12), with the largest improvement undoubtedly given by a large increase in precision when measuring the orbital decay. Not even ten years after the discovery of the system, the Double Pulsar provides the best test for the accuracy of the gravitational quadrupole emission prediction by GR far below the 0.1% level.

The fact that the size of both pulsar orbits, $x_A$ and $x_B$ could be measured, it is possible to determine the ratio of the masses pulsars A and B, $R = m_A/m_B = x_B/x_A$ in a theory-independent fashion (at least to the 1PN level, Ref. 52). In addition to the periastron advance, $\dot{\omega}$, and the gravitational redshift parameter, $\gamma$, also a Shapiro delay could be measured, which provides two PK parameters, i.e. the “shape” $s$ and “range” $r$, given in GR by

$$s = T_\odot^{-1/3} \left( \frac{P_B}{2\pi} \right)^{-2/3} x \frac{(m_A + m_B)^{2/3}}{m_B},$$

and

$$r = T_\odot m_B,$$

The shape parameter relates to the orbital inclination angle $i$, via $s = \sin(i)$, and is measured to be very close to an almost perfect edge-on configuration, which is also reflected in the observation of 30-s long eclipse of pulsar A due to the blocking magnetosphere of B. This eclipse is not perfect, but leads to the modulation of the registered emission of A, as the torus (unlike a disk) does not block the light continuously. This leaves an imprint in A’s observed flux density with a characteristic pattern, showing the emission of A every half-period of B first and later only every full-period of B, before the eclipse is over. This pattern depends on the relative orientation of B’s spin axis and therefore changes slowly due to geodetic precession.

A global fit to these eclipse pattern allowed us to determine the precession rate of pulsar B, which in GR is given by

$$\Omega_B = T_\odot^{2/3} \left( \frac{2\pi}{P_B} \right)^{5/3} \frac{m_A(4m_B + 3m_A)}{2(m_B + m_A)^{4/3}} \frac{1}{1 - e^2}.$$ 

The observed value agrees with GR’s prediction within the uncertainty of 13%. The precision of this value will improve with time, even though pulsar B is not visible at the moment. Indeed, the same precession that modulates the eclipse pattern has moved B’s beam out of our line-of-sight, so that it momentarily misses Earth.

In principle, one can write down Eqn. 6 also for pulsar A. However, geodetic precession is not observed for A. It would manifest itself in a change of the pulse
profile (as it had done for the Hulse-Taylor pulsar\textsuperscript{13,14} and pulsar B\textsuperscript{55}) but the
profile is observed to be extremely stable.\textsuperscript{56} This leads to the conclusion that the
spin axis of A is nearly perfectly aligned (within less than 3 deg) with the orbital
angular momentum vector. This in turn is evidence for a formation of B in a
low-kick supernova (Ref. 56).

6. Constraining Alternative Theories

Even though GR has been very successful in describing all experiments in the solar
system, binary pulsar tests, and now also the observed LIGO detection\textsuperscript{1} phenomena
like “dark matter” or “dark energy” may suggest deviations from GR under certain
conditions or on certain scales. Alternatives to GR are therefore discussed and need
to be confronted with experimental data. A particular sensitive test criterion is if
the theory is able to make a statement (i.e. prediction!) about the existence and
type of gravitational waves emitted by binary pulsars.

A class of alternative theories where intensive work has made this possible,
are scalar-tensor theories as discussed and demonstrated in a series of works
(e.g. Ref. 57, 58, 59). For corresponding tests, the choice of a double neutron
star system is not necessarily ideal, as the difference in scalar coupling, (that would
be relevant, for instance, for the emission of gravitational dipole radiation) is small.
The ideal laboratory would be a pulsar orbiting a black hole, as the black hole
would have zero scalar charge. But also compact pulsar-white dwarf systems can
be useful in providing constraints on alternative theories of gravity that are equally
good or even better than solar system limits (Ref. 9).

The currently best example for such a system PSR J1738+0333, a 5.85-ms pulsar
in a practically circular 8.5-h orbit with a low-mass white dwarf companion.\textsuperscript{9} The
determination of the intrinsic orbital decay due to gravitational wave emission shows
an agreement with the prediction of GR, hence introducing a tight upper limit on
dipolar gravitational wave emission. This can be translated into stringent constraint
on general scalar-tensor theories of gravity. The new bounds are more stringent than
the best current Solar system limits over most of the parameter space, and constrain
the matter-scalar coupling constant $\alpha_0$ to be below the $10^{-5}$ level. For the special
case of the Jordan-Fierz-Brans-Dicke theory, the authors obtain a one-sigma bound
of $\alpha_0 < 2 \times 10^{-5}$, which is within a factor of two of the Solar-System Cassini limit.

The relativistic pulsar-white dwarf system PSR J0348+0432 is on course to
provide better limits in the near future. The system can be studied both in the
optical (via the white dwarf emission) as well as the radio (via the pulsar).\textsuperscript{13} On
one hand, this allows to measure the mass of the neutron star, showing that it has
a record-braking value of $2.01 \pm 0.04M_\odot$. This is not only the most massive neutron
star known (at least with reliable precision), but with the also clearly measured
gravitational wave damping of the orbit, the system is a sensitive laboratory of a
previously untested part of the strong-field gravity regime. Thus far, the observed
orbital decay agrees with GR, supporting its validity even for the extreme conditions
present in the system. The recent discovery of PSR J0337+1715, a millisecond pulsar in a hierarchical triple system with two other white dwarfs offers another exciting laboratory to study in particular possible violations of the Strong Equivalence Principle. As the inner pair of pulsar and white dwarf orbit every 1.63 days in the gravitational field of an outer white dwarf (with an orbital period of 327 days), the impact of this external gravitational field on the inner orbital motion can be tested, as described previously in Ref. 61. In the near future we expect excellent limits on scalar-tensor-theories using this system (Ref. 62). See also the contribution by Archibald in this conference for more details.

Figure 1 summarizes our present constraints on a specific class of scalar-tensor gravity, which also accounts for our current imperfect knowledge of the equation of state for neutron-star matter. A summary of selected further tests of alternative theories of gravity using pulsars is given in Table 4.
Table 4. Constraining specific (classes of) gravity theories using radio pulsars. See text and also Wex (2014) for more details.

| Theory (class)             | Method                                                                 | Ref.  |
|----------------------------|------------------------------------------------------------------------|-------|
| Scalar-tensor gravity:     |                                                                        |       |
| Jordan-Fierz-Brans-Dicke   | limits by PSR J1738+0333 and PSR J0348+0432, comparable to best Solar system test (Cassini) | 9, 62 |
| Quadratic scalar-tensor gravity | for $\beta_0 < -3$ and $\beta_0 > 5$ best limits from PSR-WD systems, in particular PSR J1738+0333 and PSR J0348+0432 | 9, 62 |
| Massive Brans-Dicke        | for $m_\phi \sim 10^{-16}$ eV: PSR J1141−6545                           | 64    |

| Vector-tensor gravity:     |                                                                        |       |
| Einstein-Æther            | combination of pulsars (PSR J1141−6545, PSR J0348+0432, PSR J0737−3039, PSR J1738+0333) | 65    |
| Hořava gravity            | combination of pulsars (see above)                                     | 65    |

| TeVeS and TeVeS-like theories: | | |
| Bekensteins TeVeS          | excluded using Double Pulsar                                            | 12    |
| TeVeS-like theories        | excluded using PSR 1738+0333                                            | 9     |

7. Pulsar-Black Hole Systems

As described above, in many respects a pulsar-black hole system would be the ideal system to test theories of gravity. The pulsar could be as probe that can be used to trace the motion in the spacetime of the black hole. The first basic recipe of how to extract the black hole spin and quadrupole moment from such a system was presented by Ref. 66. It was shown that by following the orbital motion and by measuring the higher order time derivatives of the the projected semi-major axis, $x$, and the periastron angle, $\omega$, the “Cosmic Censorship Conjecture” and the “No-hair theorem” could be tested. This formed the basis of the science case for the corresponding SKA Key Science case (Ref. 22). It was later shown that measuring the spin for stellar-mass black holes was possible, but that extracting the quadrupole moment was difficult even with the SKA. Nevertheless, a stellar-mass black-hole - pulsar system would still provide a superb probe for theories of gravity (see e.g. Refs. 10, 68) and so the hunt to find such a system continues. One place where we expect pulsars to orbit a black hole is the centre of our Galaxy. The large mass of Sgr A* would also make the measurement of the black hole parameters, including the quadrupole moment, possible, as shown by Ref. 69. As shown recently by Ref. 70, it is not even necessary to measure the complete full orbit to determine the BH parameters, but measuring the pulsar around periapsis is sufficient. This
implies that certain perturbations of the orbit away of periapsis will not prevent the successful outcome of such an experiment.

7.1. Studying the super-massive black hole in the Galactic Centre

As shown in Ref 69, a slow, normal pulsar in an appropriate orbit would be sufficient to in principle measure the mass of SGR A* with a precision of a few \( M_\odot \), to test the cosmic censorship conjecture to a precision of about 0.1% and to test the no-hair theorem to a precision of 1%. This is possible even with a rather modest timing precision of 100\( \mu \)s due to the large mass of SGR A* and the measurement of relativistic and classical spin-orbit coupling, including the detection of frame-dragging. Unlike other methods, Liu et al. also developed a method that allows us to test for a possible contamination of the orbital measurements by nearby stars. Given the huge rewards for finding and timing pulsars in the Galactic centre, various efforts have been conducted in the past to survey the inner Galaxy and the Galactic centre in particular (e.g., Refs. 71, 72, 73, 74). None of these efforts has been successful, despite the expectation to find more than 1000 pulsars, including millisecond pulsars (e.g. Ref. 75) or even highly eccentric stellar BH-millisecond pulsar systems.\(^{76}\) In reality, external perturbations of the orbit (e.g. due to the presence of other stars) may limit the precision of the possible measurements. But as shown recently by Ref. 70, the repeated observations of the periapsis is sufficient to extract the information even in such cases, albeit with reduced precision.

The lack of detection was thought to be understood in terms of severely increased interstellar scattering due to the highly turbulent medium. Scattering leads to pulse broadening that cannot be removed by instrumental means and that renders the source undetectable as a pulsar, in particular if the scattering time exceeds a pulse period. The scattering time, however, decreases as a strong function of frequency (\( \propto \nu^{-4} \), see e.g. Ref. 20), so that the aforementioned pulsar searches have been conducted at ever increasing frequencies – the latest being conducted at around 20 GHz. The difficulty in finding pulsars at these frequencies is two-fold. On one hand, the flux density is significantly reduced due to the steep spectra of pulsars. On the other hand, the reduced dispersion delay, which usually needs to be removed but also acts as a natural discriminator between real pulsar signals and man-made radio interference, is making the verification of a real signal difficult.

The situation changed in 2013, when triggered by a detection of a periodic X-ray source by SWIFT and NuStar (77, 78), Ref. 79 were the first to discover a 3.8-s magnetar using the 100-m Effelsberg radio telescope only 2" away from Sgr A*. The magnetar, PSR J1745–2900, has the highest dispersion measure of any pulsar, is highly polarised and has a rotation measure that is larger than that of any other source in the Galaxy, apart from Sgr A*. The fact that a rare object like a radio-emitting magnetar may be found in such proximity to Sgr A* suggests that many more ordinary pulsar may exist. However, the magnetar also showed a scattering of emission that was far less than expected for the Galactic Centre,
begging the questions, why many pulsars, should they exist, were not yet detected after all. Solving this question is at the focus of on-going research, and by the time of the next Marcel-Grossmann meeting, new interesting results may be available.

8. Pulsars and an Image of Sgr A*

An international effort is underway to perform a mm-VLBI experiment known as the “Event Horizon Telescope” (EHT) with the aim to image the shadow of Sgr A* against the background radiation from a hot accretion disk (e.g. Ref. 80). With a mass of about $4.3 \times 10^6 M_\odot$ (e.g. Ref 81), the central BH is not very large in size compared to those in the centre of other galaxies, but it is the closest. The idea is that the precise measurement of the shadow also leads to an extraction of the black hole parameters, assuming that the shadow is determined purely by gravitational effects and that modeling does not depend on understanding of the accretion flow properties (see e.g. Ref. 80 for a recent review and contributions to this conference).

As shown recently by Ref. 70, the correlated uncertainties in the measurements of the black hole spin and quadrupole moment using pulsars are nearly orthogonal to those obtained from measuring the shape and size of the black hole shadow. Combining the different types of observations allows one to assess and quantify systematic biases and uncertainties in each measurement, which will finally lead to a highly accurate, quantitative test of the no-hair theorem. This is possible since the image and the pulsar measurements probe simultaneously the near- and far-field of SGR A*, promising a unique probe of gravity.

9. Summary

We are in a golden age of testing theories of gravity. Direct observations of GW allow to probe the dynamic strong-field regime, and allow us to probe the properties of black holes. Such tests probe a different regime that those of binary pulsars, which complement the efforts by testing self-field effects in strongly self-gravitating bodies like neutron stars. Together with direct observations of the event horizon of black holes, all experiments are therefore complementary and together probe a theory-space that will eventually inform us about the underlying theory of gravity.

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