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General Relativity support from the double pulsar

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After the final publication of the Theory of General Relativity by Albert Einstein in 1916, experimental confirmation rested on three astronomical tests. These were the amount of bending of starlight at the edge of the Sun, the change in frequency of light emanating from the gravitational field of the Sun and an explanation in terms of the theory of a remnant quantity in the perihelion advance of Mercury which had been calculated previously. The field of activity then was sparse and Quantum Mechanics attracted many scientists to its realm. However, a proliferation of renewed interest emerged 50 years on from 1916 with new thinking, improved instrumentation, the advent of spacecraft and the discovery of a number of exotic objects. The previous tests had been within the solar system. Now, there could be a transition from a weak to strong gravitational field testing. Neutron stars and pulsars were proposed based on ideas inherent within Einstein's conjecture as explanations for otherwise mysterious radio signals. In 2003, the advent of a two pulsars in mutual orbit allowed astrophysicists to delve into more precise tests of Einstein's theory. One of the parameters measured with this double pulsar has agreed with General Relativity to the 0.05% level. Three others are different from predictions by 1.4, 0.68 and 5.5%. Testing of these other parameters over a longer period of time promises to distinguish the accuracy between Einstein's ideas and concepts from other scientists.

Key words: General Relativity, neutron star, pulsar, double pulsar.

INTRODUCTION

In a review paper on relativity in 1907 Albert Einstein (1879-1955) presented an equivalence of acceleration and gravity (Einstein, 1907). From this connection, he deduced that gravitation could influence light. In particular, he submitted that light could be bent and also its frequency altered in a gravitational field. However, it was 1911 before he thought these two effects could be detected experimentally near the Sun (Einstein, 1911). Subsequently, during the development of his general theory, he determined, from his equations in 1915, a figure for the anomalous advance of the perihelion of Mercury (Einstein, 1915). In the following year he doubled his value for the amount of movement of light at the limb of the Sun (Einstein, 1916).

These three outcomes of General Relativity – gravitational deflection, the amount of Mercury perihelion increase and gravitational redshift - became the early classical tests for a new paradigm. The histories of these have been covered by the writer in two previous papers up to the year 1928 (Treschman, 2014a, b). Development after this date depended on improved instrumentation, the arrival of spaceflight and new applications from

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different modes of thinking. The period 1928 to the present has been treated by Treschman (2015) under the topics:

(a) Weak equivalence principle (equivalence of inertial and gravitational mass and gravitational redshift),
(b) Orbital precession of a body in gravitational fields (the relativistic perihelion advance of the planets, the relativistic periastron advance of binary pulsars, geodetic precession and the Lense-Thirring effect),
(c) Light propagation in gravitational fields (gravitational optical light deflection, gravitational radio deflection due to the Sun, gravitational lensing, time delay and atomic clocks) and
(d) Strong gravity implications (Nordtved effect and potential gravitational waves).

The only double pulsar (two pulsars in mutual orbit) discovered to date has provided a series of unique tests for General Relativity and represents, within the uncertainties, the smallest departure from predictions of the Einstein theory. This paper will concentrate on an analysis of data for this topic. This paper traverses the proposal from the neutron in the atom onwards to a forecast that stars could exist that would be composed entirely of neutrons. Pulsars are then investigated. An understanding of them is revealed as a result of classifying them into three groups. While binary pulsars (a pulsar in mutual orbit with an object not a pulsar) are treated, the emphasis is on the only double pulsar yet discovered, PSR J0737-3039 A and B. Observational data on this pair with the Parkes Radio Telescope in Australia in 2003 provide a highly precise test of the General Theory of Relativity. This paper uses published data to investigate what precision can be reached and how well the General Theory is supported by these observations.

NEUTRON STARS

James Chadwick (1891-1974) is credited with interpreting his experiments on firing protons and alpha particles at different elements in 1932 as evidence for a particle of mass 1 and charge 0, that is, a neutron (Chadwick, 1932). However, his former supervisor, Ernest Rutherford (1871-1937), had proposed the existence of the neutron 12 years earlier. In a lecture Rutherford outlined his radiation experiments to infer the presence in the atom of a very small nucleus surrounded by electrons. He also conjectured there were electrons within the nucleus performing a different role from those outside the nucleus. He suggested that an atom of helium consisted of four hydrogen atoms and two electrons inside giving a charge of +2 and a mass of 4, with two electrons outside. '…it may be possible for an electron to combine much more closely with the H nucleus, forming a kind of neutral doublet.' (Rutherford, 1920).

Surprisingly, within two years of Chadwick's pronouncement, (Wilhelm Heinrick) Walter Baade (1893-1960) and Fritz Zwicky (1898-1974) hypothesised that '*a super-nova* [sic] *represents a transition of an ordinary star into a body of considerably smaller mass*' (Baade and Zwicky, 1934a) and '*a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density*'. (Baade and Zwicky, 1934b)

Recent work has attempted to elicit an equation of state for neutron stars. Theoretical models have been proposed for their nature with a view to establishing limits on their masses as well as a link between the mass and radius. A typical 1.4 $M_\odot$ (mass of Sun) object would have a radius of approximately 11.5 km (Lattimer, 2012).

PULSARS

Angular momentum L is defined as

$$L = I\omega \quad (1)$$

where I is the moment of inertia and ω is the angular velocity. For a sphere

$$I = 2/5\, MR^2 \quad (2)$$

For mass M and radius R. Thus,

$$L = 2/5\, MR^2\omega. \quad (3)$$

Since angular momentum is conserved, as the radius of an object, in this case a neutron star, decreases, the angular velocity must increase. Hence, any neutron star with an initial spin was predicted to have a rapid rotation before any such object was even observed.

In addition, since the entity is expected to have a conducting fluid, a magnetic flux ought to exist. At the surface, the flux would be a product of the magnetic field strength B and the area of the surface. Again, as the neutron star shrinks resulting in a smaller surface area, B would be expected to increase.

The forecasts of a rapidly spinning, compact object with a high magnetic field became a reality in 1967 with the discovery of the first pulsar (pulsating source of radio) by (Susan) Jocelyn Bell (1943) (Hewish et al., 1968). In 1968, pulsars were connected with the Vela supernova remnant (Large et al., 1968) and the Crab Nebula relic (Staelin et al., 1968). The cause of the regular and rapid pulses had three possibilities: binary stars, pulsating stars or rotating stars. In 1969, Thomas Gold (1920-2004) dispensed with binary stars on the basis that the periods would decrease as energy was lost, contrary to the observed increase; he eliminated pulsating stars on the

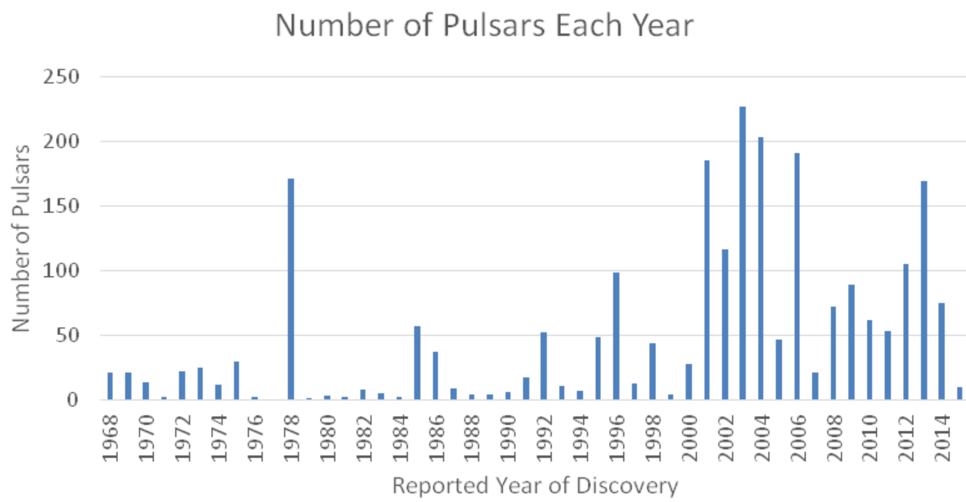

Figure 1. Number of pulsars per year of publication with later peaks due to Parkes.

foundation of the length of the period; finally, the rotation rate did not fit a white dwarf as it would fly apart at these speeds, which left, he argued, a rotating neutron star (Gold, 1969).

PULSAR SURVEYS

Large scale surveys using radio telescopes which led to the discovery of many pulsars have been conducted principally with the 100 m Green Bank Telescope in West Virginia, USA the 305 m Arecibo Observatory in Puerto Rico, the 76 m Jodrell Bank Observatory in England, the two 778 m x 12 m cylindrical paraboloids of the Molonglo Observatory Synthesis Telescope in Australia but more than half of the currently known pulsars have been identified at the 64 m CSIRO (Commonwealth Scientific and Industrial Research Organisation) Parkes Observatory in Australia (Manchester et al., 2005). The proliferation of the number of pulsars detected at Parkes is due, firstly, to the installation in 1997 of a 13 beam receiver. This multibeam pulsar survey commenced in August 1997 with each pointing of the telescope occupying 35 min duration (Manchester, 2001). In the first year of surveillance, each hour of observing time resulted in a new pulsar (Manchester et al., 2001). Secondly, the centre of the Milky Way Galaxy where pulsars are concentrated goes overhead in the Southern Hemisphere. As of May 2015, the Australia Telescope National Facility, that maintains a catalogue for the discoveries from all observatories, had listed 2405 pulsars (ATNF). These are distributed in Figure 1 by the number per year in which they were published. The peak in 1978 is due mainly to a Molonglo survey (Manchester et al., 1978) and the larger numbers in 2001, 2003, 2004, 2006 and 2013 represent surveys published principally from Parkes.

BINARY PULSARS

While theories were being advanced associating the origin of pulsars with supernovae, another development in the pulsar story was made in 1974 by Russell Alan Hulse (1950) and Joseph Hooton Taylor, Jr (1941). As they conducted a survey at the Arecibo Observatory, they detected the first binary pulsar where a pulsar and another neutron star were in mutual orbit (Hulse and Taylor, 1975). Since then, the total has reached 242 binaries where the companion may be a main sequence star, a neutron star, a white dwarf, a low mass star or another pulsar. These objects orbit each other where the range in period in the ATNF Pulsar Catalogue is from 1.6 h to 23 y.

One of the valuable outcomes from binary pulsars is that the masses of neutron stars may be determined. In a review paper by Lattimer, 33 calculated masses were shown from X-ray – optical, neutron star – neutron star and neutron star – white dwarf binaries. In this selection, the span of masses encompassed 1.00 – 1.700 $M_{\odot}$ (Lattimer, 2012).

CLASSIFICATION OF PULSARS

In 1982 a very fast rotator was timed at 1.558 ms for one spin (Backer et al., 1982). The term ‘millisecond pulsar’ was applied and encompassed any pulsar with a period shorter than 10 ms (Bhattacharya and van den Heuvel, 1991). At the other end of the spinning scale, a seemingly different type of object with pulses of 5.54 s was uncovered with the Parkes radio telescope in 2006 (Camilo et al., 2006). It was actually connected with a burst of X-rays previously detected by spacecraft in 2003. This class contains the so called magnetars and comprises anomalous X-ray pulsars and gamma ray bursters.

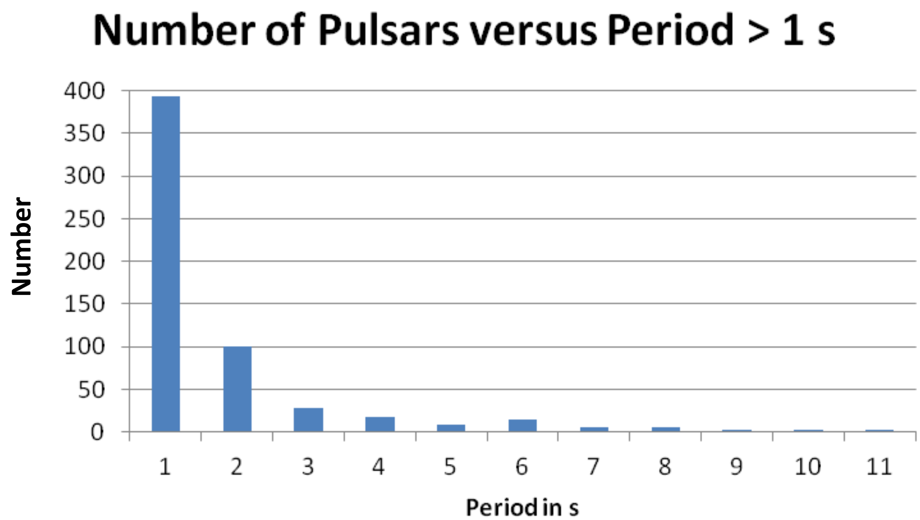

Figure 2. Number of pulsars with periods 1-12 s.

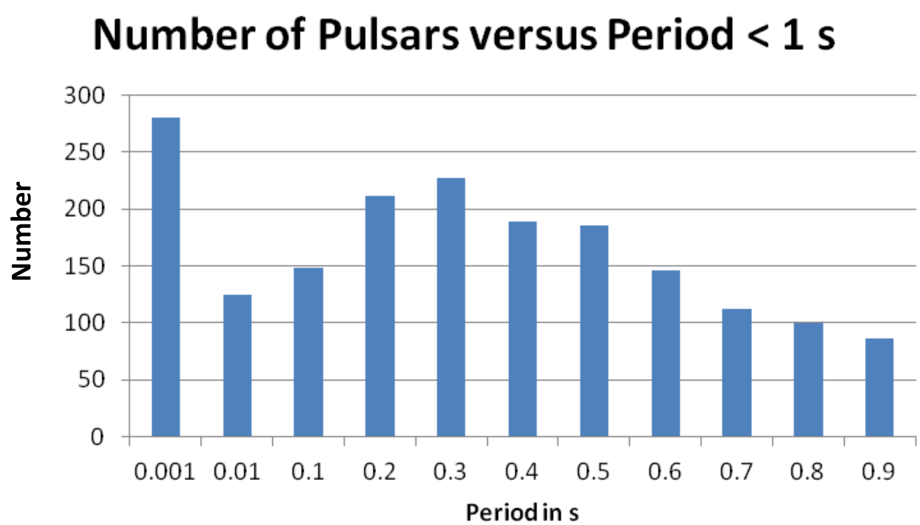

Figure 3. Number of pulsars with periods < 1 s.

From the ATNF catalogue of all known pulsars, the one with the slowest spin has a period *P* of 11.8 s and the fastest 1.4 ms, that is, over 700 times per second. Of the 2405 pulsars that have been logged, 2392 have their measured period displayed. The 581 with a period > 1 s are exhibited in Figure 2 where 1 s refers to the duration > 1 s but < 2 s and so on. For the 1811 pulsars with periods < 1 s, 1406 have a spin > 0.1 s. From an analysis of 815 pulsars, it has been estimated that perhaps 40% are born in the range 0.1 to 0.5 s (Vranesevic et al., 2004). Thus, the region 0.1 to 1.0 s has been further subdivided into 0.1 s lots as in Figure 3.

"*The pulse period is very predictable, but it is not constant. … Pulsars are powered by the kinetic energy of rotation. They steadily lose energy, mainly in the form of a high-energy wind of charged particles and magnetic-dipole radiation, that is, electromagnetic waves at the neutron star's rotation frequency* (Manchester, 2001)''. The measure of this loss of energy may be gauged in the slowdown rate of the period, $\dot{P}$ in s s^{-1}. An interesting pattern emerges if the logarithm of $\dot{P}$ is graphed against the logarithm of *P*. The plots in Figure 4 are produced from within the ATNF catalogue but here have been teased apart into the majority of pulsars, the high energy ones and the binaries respectively from left to right. The product of *P* and $\dot{P}$ leads to a measure of the magnetic field at the surface B_S as in the formula:

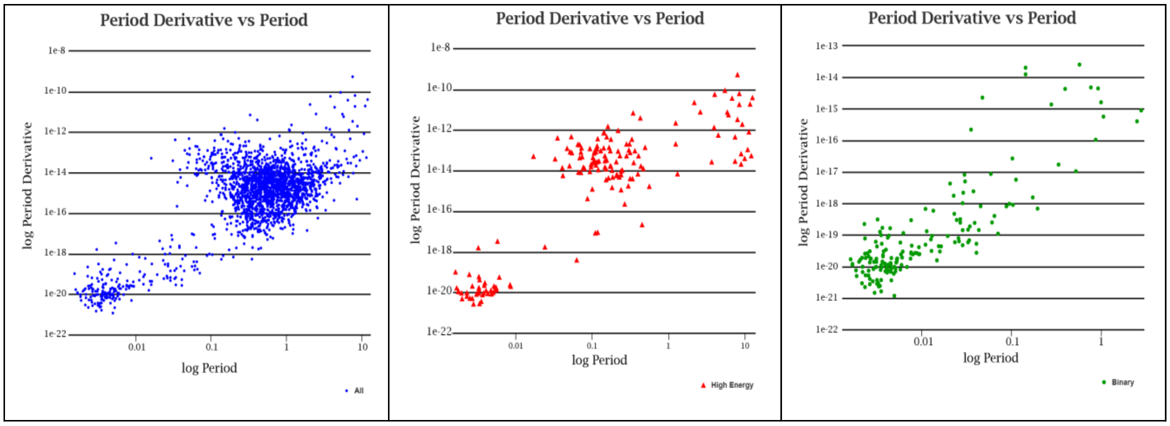

Figure 4. Log of change of period per s versus log of period for, from left, most pulsars, high energy pulsars, binaries. Note that the vertical axes are identical but the horizontal scale for the binaries is different from that of the other two.

$$B_S = (3c^2 I/8\pi^2 R^6 P\dot{P})^{0.5} \text{ in G (gauss)} \quad (4)$$

$\approx 3.2 \times 10^{19}$ $(P\dot{P})^{0.5}$ G for $I \approx 10^{38}$ kg m^2 and $R \approx 10^4$ m (Bhattacharya and van den Heuvel, 1991). For a typical high energy pulsar in the centre panel of Figure 4, 10^{19} x $(10^{-1}$ s x 10^{-13} s $s^{-1})^{0.5} \approx 10^{12}$ G. From the surface magnetic field data in the ATNF catalogue, the highest is given as 2.22 x 10^{14} G. This region embodies the magnetars which have large magnetic fields, slower rotations but faster rates of loss of energy. Also, the loss is not always uniform and is often in the form of bursts of X-rays or gamma rays. The decay of *B* powers the emission of radiation predominately in the high energy end of the spectrum. The bursts are believed to be connected with two different situations: the collapse of a star and the merger of neutron stars. From the left panel of Figure 4, a central pulsar at 10^{-1} s and change at 10^{-15} s s^{-1} has $B_S \approx 10^{11}$ G from Equation (4). They are faster rotators, have medium magnetic fields but lose their energy more slowly than the magnetars. In contrast, the binaries in the right panel of Figure 4 would have a typical result of 10^{-2} s, loss at 10^{-20} s s^{-1} for $B_S \approx 10^8$ G. The lowest value in the catalogue is 3.21 x 10^7 G. These binary pulsars are fast rotators, most reside in the millisecond class, have lower magnetic fields by comparison and lose their energy much more slowly. More than half of them have been detected in globular clusters (D'Amico et al., 2003). Their scenario is that they were older, slow rotators and even though they probably also formed from supernovae, each possessed a companion which was not ejected by this mammoth event. As the companion evolved, some of its matter accreted to the other member. The rise in angular momentum led to an increase in rotation rate of what effectively became a recycled pulsar (Possenti et al., 2004).

DOUBLE PULSAR

Where the term binary pulsar is applied to a pulsar and a companion other than another pulsar, the term double pulsar is used for two pulsars in mutual orbit. The only double pulsar system discovered to date is PSR J0737-3039A and PSR J037-3039B in the constellation Puppis, referred hereafter as A and B. The data for A were collected by Marta Burgay (1976) in April 2003 at Parkes and processed at Jodrell Bank (Burgay et al., 2003). In October of the same year, Duncan Ross Lorimer (1969) was testing code at Parkes on the data of Burgay and identified a second pulsar which was not detectable in the original records as B was only strong for two short intervals each orbit (Possenti et al., 2004). The saga is articulately presented in chapter 14 of McNamara's book on pulsars (McNamara, 2008). It was decided by the parties involved (Sarkissian, 2014) that as Burgay had already submitted for publication, it would be followed later by Andrew Lyne as principal author who was supervising Burgay (Lyne et al., 2004). Some of the physical parameters of the double pulsar are displayed in Table 1. The digit/s in parentheses following the measurement refer/s to the uncertainty in the last digit/s.

There are five orbital parameters, known as Keplerian parameters, which are required to reference the time of arrival of pulses to the barycentre of the binary system (Kramer, 2004). They are based on Newton's laws of motion and his law of universal gravitation and are calculated as an isolated two-body situation. These are shown in Table 2.

However, changes do arise due, in some situations, to the presence of other masses and, in the case of the double pulsar, to the effects of relativity. Departures from the Keplerian descriptions are referred to as post-Keplerian parameters (PKPs). Stairs explains: "*The tests of GR [General Relativity] that are possible through pulsar timing fall into two broad categories: setting limits*

Table 1. Some physical parameters of the double pulsar (Kramer, 2006a).

Physical parameter	Values
right ascension	$07^h37^m51^s.249\ 27(3)$
declination	-30°39'40".719 5(5)
spin frequency A	44.054 069 392 744(2) s^{-1}
spin frequency B	0.360 560 355 06(1) s^{-1}
inclination *i*	88°.69(-76, +50)

Table 2. Keplerian parameters of the double pulsar (Kramer et al., 2006a).

Parameter	Pulsar A	Pulsar B
orbital period P_b	0.102 251 562 48(5) d	
eccentricity *e*	0.087 777 5(9)	-
projected semi-major axis $x = a/c \sin i$ for *a*, semi-major axis	1.415 032(1) s	1.516 1(16) s
longitude of periastron from the ascending node ω	87°.033 1(8)	87°.033 1 + 180°.0
the epoch of periastron passage (MJD)	53 156.0	

on the magnitudes of the parameters that describe violations of equivalence principles, often using an ensemble of pulsars, and verifying that the measured post-Keplerian timing parameters of a given binary system match the predictions of strong-field GR better than those of other theories (Stairs, 2003)''.

Measurements are performed on the time of arrival of the pulse energy. As this signal travels through interstellar space, the presence of electrons along the path interferes differently with the frequencies so that the higher the frequency the earlier the arrival. The pulse dispersion is thus an approximate measure of distance. '*The observational parameters … are obtained from a least-squares solution of the arrival-time data …*' (Will, 2006).

ANALYSES OF DOUBLE PULSAR PARAMETERS

Stairs lists the following five equations of PKP in terms of the stellar masses (Stairs, 2003).

$$\dot{\omega} = 3\,(P_b/2\pi)^{-5/3}\,(T_\odot M)^{2/3}\,(1 - e^2)^{-1} \quad (5)$$

$$\Upsilon = e(P_b/2\pi)^{1/3} T_\odot^{2/3} M^{-4/3} M_B(M_A + 2M_B) \quad (6)$$

$$\dot{P}_b = -192\pi/5\,(P_b/2\pi)^{-5/3}\,(1 + 73/24\,e^2 + 37/96\,e^4)(1 - e^2)^{-7/2}\,T_\odot^{5/3}\,M_A M_B\,M^{-1/3} \quad (7)$$

$$r = T_\odot M_B \quad (8)$$

$$s = x(P_b/2\pi)^{-2/3} T_\odot^{-1/3} M^{2/3} M_B^{-1} \quad (9)$$

The symbol $T_\odot$ stands for the time for light to cross the radius of the Sun and is a term that allows the resultant pulsar masses to be given in terms of $M_\odot$. $T_\odot = GM_\odot/c^3 = 6.673 \times 10^{-11}$ N m^2 kg^{-2} x 1.989 1 x 10^{30} kg/(2.997 924 58 x 10^8 m s^{-1})^3 = 4.926 x 10^{-6} s. This compares closely with the literature value of 4.925 490 947 x 10^{-6} s. *x* is the projected semi-major axis of the binary orbit.

In Equation (5), $\dot{\omega}$ is the time rate of change of the longitude of periastron from the ascending node. It is the relativistic advance of periastron and is analogous to the relativistic perihelion advance of Mercury (or any other planet) in the solar system. This equation may be rearranged to provide a solution for *M*, the mass of the system which equals the sum of the individual masses $M_A + M_B$.

$$M = [\dot{\omega}/3\,(P_b/2\pi)^{5/3}\,T_\odot^{-2/3}\,(1 - e^2)]^{3/2} \quad (10)$$

Since $\dot{\omega}$ = 16.899 47° yr^{-1}, it needs to be changed into radian s^{-1}, and P_b to s. This resultant value and subsequent ones are taken from Kramer et al. (2006a). M = 2.587 08(16) $M_\odot$. Thus,

$$M_A + M_B = 2.587\ 08 \text{ or } M_B = -M_A + 2.587\ 08. \quad (11)$$

A graph of M_B versus M_A may then be drawn. As further PKPs are derived in terms of masses, these are added as graphs on the original plot. The intersection gives specific values for the masses of A and B. General Relativity may then be judged as to how constrained the quantities of the masses are. This method has an appeal

Table 3. Post-Keplerian parameters and other results of the double pulsar (Kramer, 2006a).

Parameter	Value	Equation
advance of periastron $\dot{\omega}$	16.899 47(68) ° yr^{-1}	5
gravitational redshift ϒ	0.385 6(26) x 10^{-3} s	6
orbital period derivative $\dot{P}_b$	-1.252(17) x 10^{-12} s s^{-1}	7
Shapiro delay *r*	6.21(33) x 10^{-6} s	8
Shapiro delay *s*	0.999 74(-39,+16)	9
mass of system	2.587 08(16) $M_\odot$	
mass of A	1.338 1(7) $M_\odot$	
mass of B	1.248 9 $M_\odot$	
mass ratio	1.071 4(11)	
distance based on dispersion measure	≈ 500 pc (10^{20} m)	

visually. Alternatively, two equations give two unknowns of the masses which may be solved mathematically. Then, further parameters are derived from the masses and the difference between the new parameter and its observational value provides a percentage variation for the theory of General Relativity.

Equation (6) contains the gravitational redshift parameter ϒ and is a combination of time delay and gravitational redshift. The frequency change is predicted by Einstein in that time runs differently in the region of a mass and a volume somewhat removed. It corresponds to the average amplitude of delays in arrival time due to changes in speed of the pulsars and the distance between them as they traverse their elliptical orbit. For the measured ϒ = 0.385 6(26) x 10^{-3} s, Equations (5) and (6) yield

M_A = 1.338 1(7) $M_\odot$ and M_B = 1.248 9 $M_\odot$.

The time derivative of the orbital period change $\dot{P}_b$ is caused by gravitational wave damping. Equation (7) produces a result of -1.252(17) x 10^{-12} s s^{-1}. Due to the fortuitous circumstance of the double system being almost edge on to the line of sight, the two parameters representing the Shapiro delay may also be determined (Kramer et al., 2006b). From Equation (8) the Shapiro delay *r* due to the medium of transmission is calculated as 6.21(33) x 10^{-6} s. In reverse, it is the range of the Shapiro delay that provides an estimate of the companion mass as the signal from A passes through the spacetime of B (van Straten et al., 2001).

To conclude the calculations of the PKPs, Equation (9) derives the shape of the Shapiro delay $s \equiv \sin i$ (Burgay et al., 2005) as 0.999 74(-39, +16). A further parameter which is possible with the double pulsar is to obtain a mass ratio *R* of the components by measuring the semi-major axes *a* of the elliptical orbits from the equality in the following subsequent equation.

$$R = M_A/M_B = a_B/a_A \quad (12)$$

This gives 1.071 4(11). The measurements of the PKPs from Equations (5) to (9) and data on masses and distance are summarised in Table 3. The advance of the periastron $\dot{\omega}$ has been measured to a precision approaching 10^{-5}. If this and *R* are used to solve for M_A and M_B, the values of the other four PKPs mentioned here may be calculated. This then gives tests of General Relativity as shown in Table 4 (Kramer et al., 2006a).

Departures from General Relativity are calculated here as the uncertainty in the ratio of 1.0 as a percentage. For example, for *s* the uncertainty is 0.000 50 which is 0.05%. Hence, differences from GR are 1.4% for $\dot{P}_b$, 0.68% for ϒ, 5.5% for *r* and 0.05% for *s*. This result for *s* is the most precise test ever of any technique used for comparison with Einstein's theory. The parameters $\dot{\omega}$, ϒ, *r* and *s* were obtained within seven months of observation. This level of precision of $\dot{P}_b$ followed 2.5 years of timing.

FURTHER DATA

The distance datum based on the dispersion measure is claimed to be in error by a factor of two. With measurements between 2006-2008 of the annual geometric parallax with the Australian Long Baseline Array, the figure has been given as 1 150 (+220,-160) pc (Deller et al., 2009). From the separation between the pulsars of 8 x 10^8 m, the precision of $\dot{P}_b$ is such as to be able to deduce a decreasing separation between the pulsars of 7 mm d^{-1} (Kramer et al., 2006a). After 10 more years of timing, this parameter may reach the 0.01% level.

Table 4. PKP comparisons of observed and GR predictions for the double pulsar.

PKP	observed value	GR value	ratio observed/GR
$\dot{P}_b$ s s^{-1}	1.252(17)	1.247 87(13)	1.003(14)
$\gamma \times 10^{-3}$ s	0.385 6(26)	0.384 18(22)	1.003 6(68)
$r \times 10^{-6}$ s	6.21(33)	6.153(26)	1.009(55)
s	0.999 74(-39,+16)	0.999 87(-48,+13)	0.999 87(50)

The supernova which caused the two pulsars did not throw the binary system apart but would be expected to result in a misalignment between the pulsar spin axes and their orbital axis. Geodetic precession would lead to relativistic spin-orbit coupling so that the pulsar spin axes would precess about the total angular momentum axis (Kramer, 2004; Manchester, 2010). The angular frequency period Ω_p for this is embedded in the relationship

$$\Omega_p = \tfrac{1}{2} (P_b/2\pi)^{-5/3} T_\odot^{2/3} M_B(4M_A + 3M_B)/(1 - e^2)M^{4/3}. \quad (13)$$

The calculated period for pulsar B around the total orbital angular momentum axis is 70.95 year (Manchester, 2015a). 360°/70.95 yr = 5°.074 yr^{-1}. Within an uncertainty of 13%, the precessional rate obtained of 4°.77 (+0.66,-0.65) yr^{-1} is consistent with a General Relativity prediction of 5°.073 4 ± 0°.000 7 yr^{-1} (Breton et al., 2008). From a study of eclipses of pulsar A by the magnetosphere of pulsar B, it has been inferred that the inclination of the rotation axis of pulsar B to the normal of the orbital plane is ≈ 60° and its angle to the magnetic axis 75° (Lyutikov and Thompson, 2005). Pulse profile analysis points to ≈ 90° for the difference between the spin and magnetic axes of pulsar A but only 3°.2 difference between its spin and orbital angular momentum axes (Ferdman et al., 2013). As a result, no secular change has been pursued for a measurement of the precessional period of pulsar A. Some further data given in Table 5 (Lyne et al., 2004), on the rotational periods P of pulsars A and B together with their time rates of change $\dot{P}$ may be used to calculate their surface magnetic fields and time rate of energy loss $\dot{E}$.

From Equation (4), $B_A = 6.3 \times 10^9$ G and $B_B = 1.2 \times 10^{12}$ G (Yuen et al., 2012). Also,

$$\dot{E} = -4\pi^2 I \dot{P} / P^3. \quad \text{(Manchester, 2001)} \quad (14)$$

$\dot{E}_A = 5.9 \times 10^{26}$ W and $\dot{E}_B = 1.6 \times 10^{23}$ W where 1 W ≡ 10^7 erg s^{-1} (Yuen et al., 2012). Some concept of the dense nature of a pulsar may be gauged by comparison with the atomic nucleus. With the masses of pulsar A and a neutron being respectively 1.338 1 $M_\odot$ and 1.674 928 6 x 10^{-27} kg, on the assumption that pulsar A were comprised totally of neutrons, there would be of the order of 10^{57} neutrons present. The density of pulsar A, taking the radius as 1.15 x 10^4 m, would be 4.2 x 10^{17} kg m^{-3} compared with that of an atomic nucleus of 2.3 x 10^{17} kg m^{-3}. The designation neutron star is truly appropriate.

Table 5. Parameters for spin periods and their time rates of change.

Parameter	Observed value
P_A	0.022 699 378 556 15(6) s
$\dot{P}_A$	1.74(5) x 10^{-18} s s^{-1}
P_B	2.773 460 747 4(4) s
$\dot{P}_B$	0.88(13) x 10^{-15} s s^{-1}

FUTURE

As a result of the dynamic changes in the double pulsar system PSR J0737-3039A/B, the beam of pulsar B ceased sweeping across Earth in 2008. However, it is expected to again intersect Earth in the near future (Manchester, 2015b). The longer the time span of observations, the more precise the measurements of this system become. This places tighter constraints on the parameters and provides a more stringent test of General Relativity or competing theories.

Radio receivers are the instruments which provide accurate measurement of timing for pulsars. Nevertheless, other realms of the electromagnetic spectrum may elucidate data that give a more detailed picture of the operation of the double pulsar. In 2006, the Chandra X-ray Observatory collected data on the system at this high energy end and the interpretation was that it showed that the emission was due to the shock from pulsar A interacting with the interstellar medium (Granot and Mészáros, 2004). Later, in 2012, the Hubble Space Telescope acquired images in the far ultraviolet region (Durant et al., 2014).

A 500 m radio telescope is slated for first light in China in 2016. A stated objective of this project is an emphasis on collecting information on more distant pulsars (Nan et al., 2011). When the Square Kilometre Array begins its operation, it also has targeted pulsar surveys with an emphasis on the millisecond variety (Carilli and Rawlings, 2004) with improved timing precision (Shao et al., 2014).

As a larger collection of pulsar, binary pulsar and double pulsar samples increases, measurements of moments of inertia will allow a deeper insight into the nature of superdense matter (Kramer et al., 2006a).

One of the pursuits in pulsar investigation is the detection of gravitational waves which are predicted by General Relativity. The amount of release of energy is consistent with the theory but the instrumentation available today is not sensitive enough to detect and measure it. When a figure was forthcoming for the merger rate of the double pulsar of 85 x 10^6 yr (Burgay, 2011), the expected rate of binary pulsar collisions increased dramatically. This gave greater impetus to the likelihood of detecting this far greater amount of energy. The Laser Interferometric Gravitational-Wave Observatory (LIGO) in the United States of America, the Japanese TAMA project, German-British GEO detector in Germany and the European Gravitational Observatory in Italy have embarked on the quest to discovery such a phenomenon (Abbott et al., 2009).

This prominence given to increasing the precision of measurements is not just about discriminating between rival theories for understanding the Universe. General Relativity has passed with flying colours any test thrown at it. However, it started in 1915 as a theoretical construct without any experimental support. Scientists ''*did not dream that transition to a relativistic system would have observational consequences* (Kuhn, 1962, 2012)''. The situation morphed when it was realised that there were three 'classical' predictions upon which its mettle could be judged. Even then, the field was quite dormant. Interest was piqued 50 years after the formulation of the theory as new thinking was applied, instrumentation progressed, the space era had begun and more exotic objects started presenting themselves in the cosmos. Up to this point, it could be seen that Newton's laws could still be applied with Einstein filling in when speeds increased into the regime of the speed of light or masses became somewhat larger than that of the Sun. However, the application of General Relativity in the confines of the solar system, known as the weak field situation, completely trumps Newtonian theory in the strong fields of, for example, pulsars. A paradigm shift ensued. Where might General Relativity lead us? Just as the extent of its applicability was not predictable, the theory needs to be mined for what else it may elucidate. As one sign of the dramatic change, one may look at a criterion for a paradigm shift in conferences held specifically in a field. The first international convocation completely devoted to General Relativity was in 1955, a few months subsequent to Einstein's death. These are now held each three years, with 21 having occurred. Now, at the 100 year anniversary of General Relativity, the field is still providing promise for many scientists.

CONCLUSION

The prediction of superdense forms of matter predated the recognition of neutron stars. With the arrival on the scene of pulsars in 1967, an entire new field emerged and General Relativity was the guiding post to scientific understanding. Entering the scene in 1974, binary pulsars extended the possibilities and precision of measurement. In 2003, the discovery of a double pulsar has provided scientists with a unique gamut of prospects in the strong field arena. Astronomical tests of General Relativity have included inertial and gravitational equivalence, gravitational redshift, relativistic perihelion and periastron advance, geodetic precession, light propagation in gravitational fields and implications in strong gravity regimes. Of all of these, the most accurate figure to date of 0.05% for the departure between observation and General Relativity comes from a parameter of the double pulsar PSR J037-3039A/B.

Conflict of Interest

The authors have not declared any conflict of interest.

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