The first-ever double-pulsar system was discovered by radio astronomers two years ago and has provided the sternest test of general relativity to date

Gravitational labs in the sky

Andrew Lyne and Michael Kramer

RARELY has a single event changed our view of the universe as much as the solar eclipse of May 1919. With the Sun's light blocked by the Moon, Sir Arthur Eddington and colleagues observed that stars close to the Sun appeared to have moved slightly from their usual positions in the sky. This confirmed a prediction of the general theory of relativity – that massive bodies can bend light – which overturned Newton's 200-year-old theory of gravitation and propelled Albert Einstein to global stardom.

Today, 86 years after these historic observations, general relativity is still passing all observational tests with flying colours. But never satisfied, and perhaps suspicious of "flawless theories", astronomers have been striving to test the theory under ever more extreme conditions. That quest recently received a huge boost when researchers discovered a double pulsar, a pair of cosmic "clocks" that are orbiting one another, that can be used to make stringent tests of gravitational theories.


CSIRO

An ear to the stars – astronomers discovered the first double pulsar in late 2003 using the 64 m Parkes radio telescope in Australia (above), which was previously used to relay the pictures of the first Moon landings. The radio emission from a double pulsar is a powerful tool for testing the predictions of general relativity.

Changing times

Pulsars are neutron stars – extremely small and dense collapsed stars – that can rotate up to nearly 700 times a second. They are highly magnetized and emit beams of radio waves as relativistic particles stream out of their magnetic poles. These beams rotate with the star, and are therefore observed as pulses of radio waves, as if the pulsars were cosmic lighthouses. The period of a pulsar is extremely stable and so it can be used as a highly accurate cosmic clock.

Astronomers can use this timekeeping ability to map out a pulsar's orbit. As the pulsar moves away from an observer its signals take progressively longer to reach their destination and the pulsar-clock appears to run late by the extra time the pulses take to travel. Conversely, as the pulsar-clock moves towards an observer, it appears to run early. The orbit of a pulsar can therefore be mapped using variations in the arrival times of its pulses.

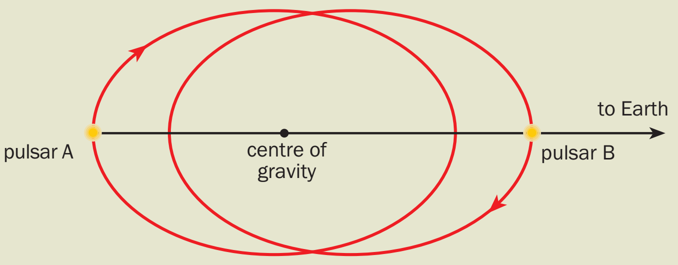
This technique has already led to a number of important gravitational measurements, most notably the observation of a slow but gradual shrinkage of the orbit of the pulsar in the binary system PSR B1913+16 (this binary consists of two neutron stars orbiting around a common centre of mass). Discovered by Russell Hulse and Joe Taylor in 1974, this system provided indirect proof for the existence of gravitational waves – ripples in space–time that general relativity predicts are produced by accelerating masses. These gravitational waves should carry energy away, causing the two companion stars to spiral into one another and eventually collide to form a black hole.

This work was a major vindication of general relativity and earned Hulse and Taylor the 1993 Nobel Prize for Physics. But the recent discovery of a double pulsar will provide a much sterner test of Einstein's theory. PSR B1913+16 contained only one neutron star that was identifiable as a pulsar, and therefore only one source of data about the size of the binary. But with the double pulsar, called PSR J0737-3039, we can measure changes to the orbits of both objects (see figure 1). With one pulsar rotating once every three seconds and the other 44 times a second, and with each weighing nearly a million times the mass of the Earth but measuring only a few tens of kilometres across, this system offers physicists the gravitational laboratory of their dreams.

An astronomical holy grail

The discoveries of a double pulsar and of a pulsar orbiting a black hole have long been considered "holy grails" in the effort to test general relativity. In 1997 astronomers at the Jodrell Bank Observatory in the UK, the universities of Palermo and Bologna in Italy, the Australia Telescope National Facility and, more recently, the Cagliari Astronomical Observatory, also in Italy, set up an international collaboration to search for such systems. To maximize the chances of making a discovery, researchers in the collaboration developed a new type of radio receiver that can monitor 13 independent regions of the sky at the same time. Installed on the 64 m Parkes radio telescope in Australia, this receiver has allowed us to observe for much longer periods than before, and therefore to probe deeper into space.

1 The double pulsar PSR J0737-3039A



The two pulsars in the binary system both trace out elliptical orbits and share a common "focus" at the centre of gravity. The pulsars complete one cycle every 2.4 hours and have a separation of 700 000 km.

A gravitational test-bed

The following five "post-Keplerian" relativistic parameters have been measured in PSR J0737-3039, which all cause slight modifications to the arrival times of the pulsars' radio pulses.

Relativistic periastron advance, $\dot{\omega}$
This is the rotation of the line connecting the two pulsars at their closest approach. It arises from the distortion of space–time caused by the two stars, but can also be understood as the result of the finite time needed for the gravitational influence of one star to travel to the other. This causes a time delay, during which the stars move and the attractive force between them is no longer radial.

Gravitational redshift, γ
This arises from time dilation in a gravitational potential well, causing clocks close to a neutron star to tick more slowly than those further away. In other words the pulse rate for PSR-A will slow down as it passes close to PSR-B, and vice versa.

Shapiro delay, r and s
Radiation passing a massive body is delayed because its pathlength is increased by the curvature of space–time, an effect that Einstein overlooked but that was discovered by Irwin Shapiro in 1964. Signals from PSR-A are measured as they pass through the distorted space–time of PSR-B (in principle the effect could also be measured for the signals from PSR-B, but these pulses are much broader and do not provide sufficient temporal resolution). The signal delay is essentially a function of two parameters: s, the shape, and r, the range of the spatial region in which the signals are delayed (with s being dependent on the inclination of the pulsar orbits and r on the mass of PSR-B).

Gravitational radiation and orbital decay, dP_b/dt
Almost every theory of gravitation predicts that the movement of massive bodies around one another in a binary system results in the emission of gravitational waves. This emission causes the bodies to lose energy, spiral in on one another and eventually merge, creating a burst of gravitational waves when they do so. The Anglo–Italian–Australian collaboration has discovered that the orbits of the pulsars are shrinking by about 7 mm per day, suggesting that PSR-A and PSR-B will merge in about 85 million years' time. This timescale suggests that the current generation of gravitational-wave observatories will detect bursts of gravitational waves from colliding neutron stars once every few years.

The results have been most rewarding. When the collaboration first started using the "multibeam" receiver eight years ago, 730 pulsars had been discovered and the Hulse–Taylor system still provided the most extreme test of general relativity. Today, thanks to the significant human effort of those in the collaboration, powerful instrumentation and access to a large portion of the Milky Way, there are now more than 1700 known pulsars. But few, if any, of these discoveries compare to that of PSR J0737-3039.

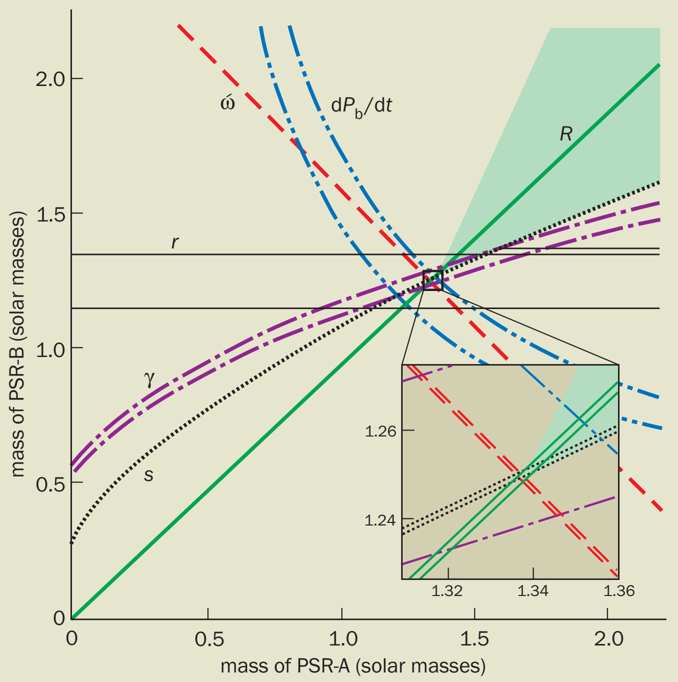
In April 2003 Marta Burgay, a PhD student at Bologna, discovered an interesting-looking pulsar with a spin period of 23 ms among the endless Parkes data processed by the supercomputer at Jodrell Bank. It immediately became clear that the interval between the radio pulses of PSR J0737-3039A, as the pulsar was named, was varying rapidly. This suggested that it was a member of a close binary system, with its signal undergoing the varying Doppler effects caused by the gravitational pull of a nearby and relatively massive companion. Follow-up observations soon confirmed that the pulsar was indeed in a very compact, slightly elliptical orbit with a period of only 2.4 hours. With a diameter of about 700 000 km – just half the diameter of the Sun – the pulsar's orbit is less than a third of the size of the next largest orbit of any known binary pulsar.

The orbital parameters of the pulsar indicated that its companion was at least 20% more massive than the Sun. Given such a high mass, we were confident that the companion was another neutron star. (To have such a mass, a normal star would be bigger than the orbit of the pulsar.) Intriguingly, we also found that the pulsar was not returning to exactly the same point in space after completing one orbit. The orbit was "precessing", with the periastron – the line drawn between the pulsar and its companion at their closest approach – rotating by about 0.05 degrees per day, or 17 degrees per year. This is a well-known prediction of general relativity: its explanation of a much smaller precession (just 0.00012 degrees per year) in Mercury's orbit around the Sun had been one of the first triumphs for Einstein's theory. At that moment we knew we had found something special, but little did we know what still awaited us.

After having observed the pulsar for about six months, and with the publication of its discovery well under way, one of the present authors (MK) was woken at 5 o'clock on the morning of 18 October 2003 by Duncan Lorimer at the Parkes facility. Lorimer and colleagues had been shocked to discover that the binary had a second strong pulsed signal, with a period of about 2.8 s, and, understandably, Lorimer could not wait to give us the news. The companion was a pulsar! The new pulsar had Doppler variations in its signal that identified it, without any doubt, as the companion of PSR J0737-3039A (or "PSR-A"). We had discovered the first ever double-pulsar system. Further investigation explained why we had missed the second pulsed signal in earlier analyses – this signal is only strong enough to be detectable for about 20 minutes during each orbit.

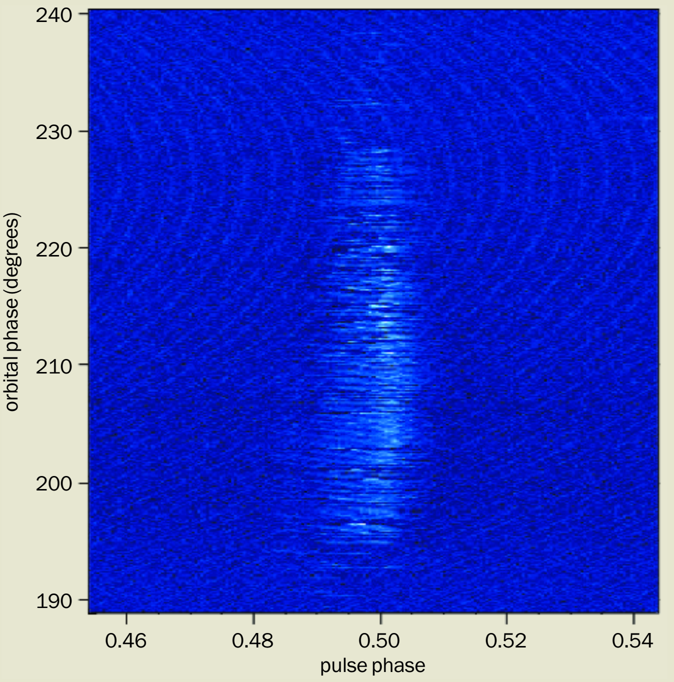
With this discovery, a race was suddenly on. It was clear to us that as soon as our colleagues elsewhere in the world read our paper announcing the discovery of the first pulsar, they would use all available telescopes to observe it. The question was, how long would it take them to discover the signals from the second pulsar (PSR-B)? Putting all other interesting discoveries aside, we tried to learn everything about PSR-B and

2 Proof that Einstein was right



Any theory of gravitation will generate a number of functions linking the (unknown) masses of the two pulsars in a binary system, each function containing a different post-Keplerian parameter. This figure shows the general-relativistic functions associated with the $\dot{\omega}$, γ, r, s and dP_b/dt post-Keplerian parameters, as well as the Keplerian ratio, R (which is the ratio of the sizes of the pulsars' orbits), for the pulsars PSR J0737-3039A and B. The two plots for each function indicate the uncertainty in the observed values of the Keplerian and post-Keplerian parameters. The fact that all of the functions (within their uncertainties) meet at a single point vindicates general relativity: the values of the masses at this point are the actual masses of the pulsars. (The geometry of the pulsars' orbits dictates that the intersection point must lie within the green region in the top right-hand corner of the graph.)

3 The double-pulsar emission



This graph shows a small portion of PSR-B's pulse period across a 50 degree section of its orbit. Its pulse generates the vertical band of horizontal lines in the middle of the graph, which has been corrected for the Doppler effect. The fact that the band is cut off at the top and bottom indicates that the emission from PSR-B varies throughout its orbit. This asymmetry is probably caused by charged particles and electromagnetic waves from PSR-A blowing away some of the magnetosphere of PSR-B. The Anglo–Italian–Australian collaboration did not observe this emission initially because it was looking in the dark regions. PSR-A's pulse, meanwhile, is seen in the curved lines running across the graph. The fact that there are a number of these lines indicates that PSR-A has a higher pulse rate than PSR-B, while the varying spacing of these lines indicates the Doppler shift of PSR-A's signal.

its possible interaction with PSR-A as quickly as possible. Indeed, the potential of this first double-pulsar system soon became clear. In addition to being an incredible test-bed for gravitational physics, we realized it could teach us much more about pulsars themselves.

Relativistic test-bed

Most binary orbits are elegantly and precisely described by their five Keplerian orbital parameters, based simply on the inverse square law of gravity. These parameters specify the size, shape, period and orientation of the orbital ellipse. However, a number of relativistic corrections to this classical description of the orbit – the so-called post-Keplerian (PK) parameters – are needed if the gravitational fields are sufficiently strong. In only a few months, using the Parkes telescope and the Lovell Telescope at Jodrell Bank, we have already measured several relativistic effects that took years to measure with the Hulse–Taylor system (see box on page 30).

These effects can be used to carry out the elegant test of general relativity described by Thibault Damour of the Institut des Hautes Etudes Scientifiques in Paris and Taylor, now at Princeton University. In 1992 Damour and Taylor showed that in any reasonable theory of gravity each PK parameter can be written as a function of the mass of the neutron stars, which are not known, and the Keplerian orbital parameters, which can be measured. In other words, for each PK parameter there is a unique relationship between the two masses of the system. So by inserting the measured value of each PK parameter into the associated equation linking the two masses, one can plot the masses of PSR-B for a range of values of PSR-A (see figure 2). For a theory of gravity to be correct, all five plots have to meet at a single point: the actual values for the masses of the pulsars.

To date, such tests have been carried out in two double-neutron-star systems: PSR B1913+16 by Taylor and Joel Weisberg of Carleton College in the US; and PSR B1534+12 by Ingrid Stairs of the University of British Columbia in Canada and collaborators. However, in the double-pulsar system we gain an additional parameter because we can measure the orbits of both objects with high precision. This is thanks to Kepler's third law, written in the 17th century and still valid today, which states that the ratio of the masses is inversely proportional to the size of the orbits: a more massive object is pulled less by its less-massive companion. For a given binary system this mass ratio will be fixed, resulting in a straight line plot (which is independent of any theory of gravity). The intersection point of all the other curves must therefore lie on this line. As figure 2 shows, the measurements carried out on PSR J0737-3039 are fully consistent with general relativity, further demonstrating Einstein's remarkable insight.

We are also able to obtain the masses of the neutron stars with very high precision. Our calculations after only six months of observation reveal remarkable precision, indicating a figure of 1.337 ± 0.005 solar masses for PSR-A and

1.250 ± 0.005 solar masses for PSR-B, which is the lightest neutron star ever discovered. Plugging these values back into the parameter functions then allows us to calculate the value of each parameter. For instance, the ratio of the value of the Shapiro parameter, *s*, predicted by general relativity to that observed is 1.001 ± 0.002.

This value of *s* also shows that the orbit of the PSR J0737-3039 system is within 2 degrees of being edge-on as seen from Earth. This result was confirmed a few months after the discovery by Scott Ransom and collaborators using the Green Bank Telescope in West Virginia.

Probing the plasma

The double pulsar provides an unprecedented opportunity to probe the workings of pulsars and their magnetospheres – the regions of space around pulsars in which the radio emissions are generally created. The radio emissions from both pulsars in PSR J0737-3039 are of great interest to astronomers because they vary in ways not seen before. The emission from PSR-B varies systematically as it traces out its orbit, probably because a wind of charged particles and powerful electromagnetic radiation emerging from PSR-A blows away about half of the magnetosphere of its partner, resulting in an asymmetrical emission of radio waves (see figure 3). In particular, Maura McLaughlin at Jodrell Bank and colleagues have shown that the emission from PSR-B is modulated once every 22.7 ms, probably by electromagnetic radiation with a frequency of 44 Hz emitted by PSR-A.

Conversely, the emission from PSR-A disappears for about 30 s in each orbit. This occurs when PSR-A disappears behind PSR-B, so it is clear that the signal from PSR-A is being absorbed by the relativistic plasma surrounding its partner (see figure 4). This eclipsing of PSR-A is possible because the orbits of the binary system happen to be almost exactly edge-on as seen from Earth, and means that we can probe the structure and density of the magnetosphere of PSR-B using the PSR-A signal. This is the first time such a feat has been possible. Indeed, it is clear that the degree of eclipsing depends on the orientation of PSR-B's magnetic poles as it passes in front of PSR-A, allowing us to measure the transparency of PSR-B's magnetosphere as a function of the pulsar's orientation.

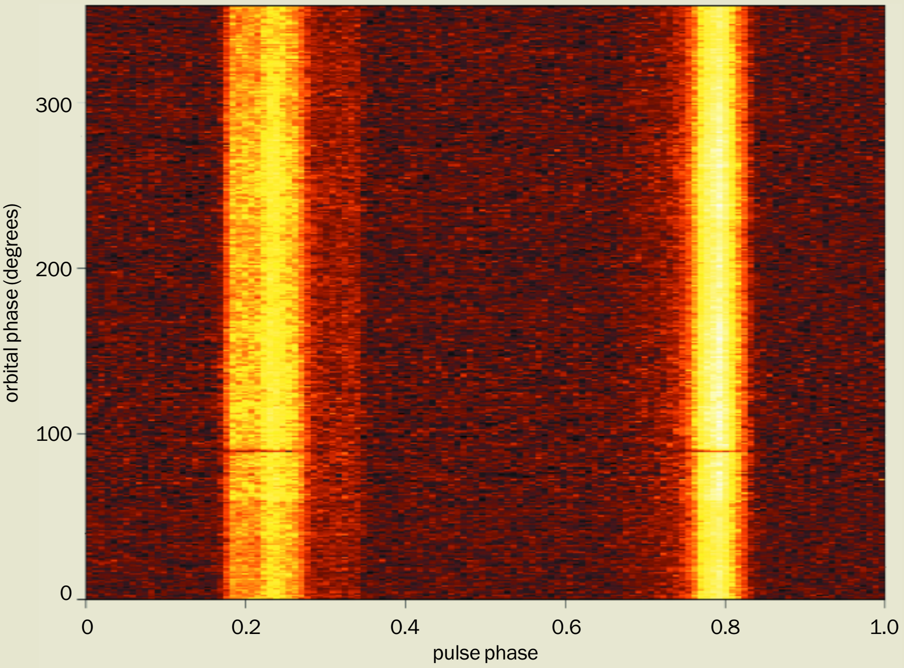
Never satisfied

Future observations of binary systems like PSR J0737-3039 promise to greatly increase our knowledge of gravity, but finding these systems will be a challenge. This is because double pulsars are extremely rare and, more importantly, because the Doppler effect causes their pulse periods to vary rapidly even during a short observation. It therefore becomes more difficult to identify a pulsar's faint emission above the background noise of space by looking out for its regular pulse structure.

Discovering a black-hole/pulsar binary will be even more challenging than identifying double pulsars since the huge acceleration caused by a black hole will generate even larger Doppler variations. But these conditions also make the rewards that much greater, since these systems will provide an even stricter test of general relativity.

For general relativity to survive this test would provide further vindication of an already extremely successful theory. But we cannot take this success for granted. Newton's view of the universe was finally removed from its pedestal by Eddington's pioneering observations, and we carry on in our work with the belief that one day, perhaps, we might also unseat Einstein.

4 Pulsar eclipse



The radio pulses emitted by PSR-A actually come in two parts, occurring about one-fifth and four-fifths of the way through each rotation of the pulsar (seen here as bright stripes). The thin dark horizontal lines crossing the stripes at the 90 degree point in PSR-A's orbit occur when PSR-A passes behind PSR-B and its emission is absorbed by its partner's magnetosphere. This eclipse lasts for about 30 s.

Further reading

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Andrew Lyne and **Michael Kramer** are at the Jodrell Bank Observatory, University of Manchester, UK, e-mail agl@jb.man.ac.uk and mkramer@jb.man.ac.uk