ASTRONOMY

Double Pulsar Jackpot

Edward P. J. van den Heuvel

Pulsars, discovered in 1967 by Jocelyn Bell and Anthony Hewish, are rapidly spinning neutron stars whose lighthouse-like beams of radio waves sweep Earth, producing highly regular radio pulses. The steadiness of the pulses makes pulsars very accurate clocks, rivaling the best atomic clocks on Earth. At present, more than 1500 radio pulsars are known in our Galaxy, and a few have been found in nearby galaxies such as the two Magellanic Clouds. On page 1153 of this issue, Lyne *et al.* (*1*) describe an exciting discovery—two pulsars orbiting each other every 2.4 hours, one of them even briefly eclipsing the radio waves from the other during each orbit.

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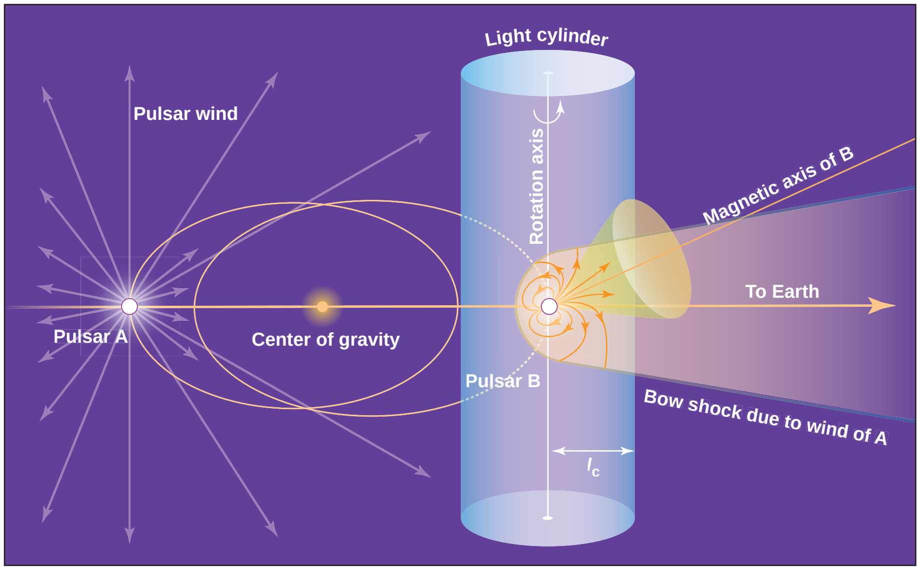
Neutron stars and black holes are the most compact objects known in nature and have the strongest gravitational fields. They are formed by the collapse of the burned-out core of a massive star, accompanied by a supernova explosion in which the envelope of the star is violently ejected. With a mass some 400,000 times that of Earth and a diameter not larger than that of New York City, a neutron star is essentially a giant atomic nucleus, held together by gravity. The gravitational attraction at its surface is some 11 orders of magnitude greater than on the surface of Earth.

Finding an accurate pulsar "clock" orbiting another neutron star is a fantastic gift of nature that provides a unique laboratory for testing with high precision many of the strange predictions of Einstein's theory of general relativity. Among the predictions are that time slows down in a strong gravitational field, that the space-time around a neutron star is curved, and that accelerated massive bodies emit gravitational waves. All these effects have been verified with high precision in the first binary pulsar system PSR B1913+16, discovered by Hulse and Taylor in 1974. For the measurement of the orbital shrinking of this system due to the emission of gravitational waves (exactly as predicted by Einstein's theory) and for the first time proving the existence of these waves, Hulse and Taylor were awarded the 1993 Nobel Prize in Physics (*2*). Similarly, the 900,000-km orbit of the new system is expected to be shrinking by about 7 mm per day as a result of the emission of gravitational waves. This effect is expected to be measurable within a few years.

In the Hulse-Taylor system as well as in the other half-dozen double neutron stars discovered in the past 30 years, only one of the neutron stars is a pulsar. The conclusion that the unseen other star in these systems is also a neutron star is derived from a variety of indirect arguments—for example, from the fact that their orbits are elliptic in combination with the theory of binary stellar evolution [see (*3*–*5*) and below]. That the other star in the new system is a pulsar confirms these theoretical arguments.

The discovery of the first pulsar in the new system, now called PSR J0737-3039A after its coordinates in the constellation Puppis, was announced by Burgay *et al.* (*6*). This discovery caused great excitement in the gravitational wave community because the very narrow orbit of this system implies that the rate at which neutron stars collide and produce enormous bursts of gravitational waves—detectable with antennae on Earth—must be much higher than had been expected (*6*, *7*). The first pulsar is a neutron star spinning 44 times per second around its axis, with a surface magnetic field of about 7×10^9 G (gauss), weaker than that of normal single pulsars by a factor of several hundred (for comparison, the strength of Earth's magnetic field is about 0.5 G).

Further study of the data by the discovery team revealed the presence of a second periodicity in the data, with a period of 2.8 s. This proved to be the rotation period of the second neutron star, now called PSR J0737-3039B, which appears to have a magnetic field of "normal" strength for a pulsar: 6×10^{12} G. The value of the surface magnetic field strength is inferred from the measured rate of increase of the pulse period of a pulsar. The cause of this "spin down," which is observed in all radio pulsars, is the electromagnetic wave (known as magnetic dipole radiation)



Two-pulsar dance. Schematic of the double pulsar system (not to scale) relative to observers on Earth. The ellipses are the orbits of the two pulsars A and B around the common center of gravity seen at an oblique angle. Pulsar A's strong outflow of relativistic particles and magnetic fields ("pulsar wind") penetrates into the light cylinder of star B and causes the formation of a bow shock with a long tail behind pulsar B. The light cylinder (with radius l_c) plays an essential role in the generation of the radio beams that cause the observed pulsed signal. The beam of pulsar B is depicted here as a hollow cone centered on the magnetic dipole axis. The disruption of pulsar B's light cylinder on the side facing pulsar A may short-circuit the currents in B's magnetosphere that produce the radio beams, which might explain the weakness of the pulses of B observed over most of its orbital cycle. Changes in orientation of the light cylinder will cause variations in the emitted beam, as will relativistic precession of the rotation axis.

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produced by the rotation of a magnet. This wave is filled with an electron-positron pair plasma, the "pulsar wind." Together, the emission of this very strong wave in combination with the acceleration of the wind particles to highly relativistic velocities occurs at the expense of the neutron star's rotational energy. This allows one to calculate the magnetic field strength from the pulse period in combination with the measured rate of increase of the pulse period of the pulsar (*8*, *9*).

With the discovery of the second pulsar in the PSR J0737-3039 system, the orbits of both stars should now be measurable with high accuracy. This in turn will allow, as Lyne *et al*. also point out (*1*), more precise tests of Einstein's general theory than were possible in the Hulse-Taylor system and other double neutron star systems. It helps that this system is much closer to Earth (only 1500 light years), which reduces the possible errors in the measured rate of orbital shrinking (caused by emission of gravitational waves) introduced by unknown galactic rotation effects. Furthermore, because the orbital plane happens to nearly coincide with our line of sight (see the figure), the radio waves of pulsar A occasionally shine through the much larger plasma-filled magnetosphere of pulsar B. This produces an "eclipse" of A's radio emission for a few tens of seconds, and it provides a unique way to probe the still largely unknown properties of pulsar magnetospheres. One complication here may be the fact that pulsar A is 3600 times as energetic as pulsar B; hence, its energetic pulsar wind may be blowing away part of the plasma-filled magnetosphere of pulsar B, causing its radio emission to be weakened. A clear sign of this energetic interaction is that during most of its orbital motion the B pulsar is hardly visible, becoming very bright only during two time intervals of about 10 min each when it is near the Earth-facing side in its orbit.

How did such a pulsar system evolve? Like other pulsars in binary systems, PSR J0737-3039A has an abnormally rapid spin and an abnormally weak magnetic field, weaker than that of "normal" single pulsars by a factor of about 200 (see above). According to the current models for the formation of these systems (*3*–*5*, *10*), the faster pulsar is the first-born neutron star, which later in life—when its companion was still an ordinary star—had matter dumped onto it by its swelling companion giant star. This accretion of matter weakened its magnetic field (*11*) and accelerated its spin (*4*). Later, the neutron star entered the envelope of the giant, and the ensuing large friction caused the orbit to become very narrow. After the giant's hydrogen envelope was expelled, a very close binary in a circular orbit was formed, consisting of the neutron star and the heavier-element core of the giant star. When this core collapsed it became the second neutron star in the system, and its remaining mass was ejected in the accompanying supernova event. Because the second-born neutron star in the system did not undergo any further evolution with mass transfer, it would be expected to be an entirely "normal" strong-field pulsar with a "normal" pulse period on the order of about 1 s, just as observed for most of the single radio pulsars in the galaxy. PSR J0737-3039B nicely fits these expectations, providing confirmation of this standard evolutionary model. The "old" neutron star in the system, which underwent a history of magnetic field decay and "spin-up" by accretion in a binary, restarted its life as a rapid pulsar and is therefore called a "recycled" pulsar (*12*). All pulsars observed in the double neutron star systems, with the exception of PSR J0737-3039B, appear to be such recycled pulsars. Their weak magnetic fields make them spin down much slower—and therefore "live" much longer as pulsars—than their newer strong-field companions, which explains why these are so rarely observed (*5*).

Much more remains to be learned about this surprising pair of stars. This binary pulsar is a rich gift of nature, holding much promise for workers in fields as diverse as general relativity and gravitational waves, pulsar emission theories, and the theory of binary stellar evolution.

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NEUROSCIENCE

The Where and When of Intention

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> *Intention is judge of our actions.*
>
> –Michel de Montaigne

At a moment of your own choosing, snap your fingers. Now ask yourself: "When did I first feel the urge—or intention—to make that snap? Was it a full second before my fingers moved?" Although that duration might seem counterintuitive, human brain studies using electroencephalography (EEG) have long suggested that some part of your brain was already moving toward that decision well before you were aware of it. Spontaneous, voluntary movements are preceded by a progressive rise in motor area activity known as the readiness potential (RP) (*1*–*4*) more than a second before you make your move (see the figure). Although we are subjectively unaware of this buildup of activity, does this mean that we are not aware of anything before our fingers suddenly jerk into motion? Or do we have some sense that we are about to act, some notion of intention just before our bodies begin to move?

To explore this issue, one set of early experiments asked participants to make a spontaneous finger movement—at a time of their choice—while watching a spot moving around a clock face. Subjects were asked to report the time at which they first felt the urge to move. Their typical answer: ~200 to 250 ms before the time of their actual movement (*5*). This experimental design has had a long and often controversial history—after all, how do we know subjects aren't simply attending to the beginning and end of the same movement, or deciding that the time of their intention logically must precede the time of their action? Given these uncertainties, it has remained unclear whether the urge to act, and the action itself, represent actual differences in brain states. Onto this stage enter Lau *et al*. (*6*), on page 1208 of this issue, with a functional magnetic resonance imaging (fMRI) experiment that directly addresses this question.

In Lau *et al*.'s study, participants made a spontaneous finger movement and reported the time at which they first felt aware of the intention to move (I-condition) or they actually moved (M-condition). In line with previous findings, subjects reported the urge to move an average of ~200 ms before

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