Stellar pulses

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Atomic clocks can presently measure time with an accuracy down to 10^{-10} second per day. However, there are certain stars that can easily match them as excellent timekeepers...

The first pulsar, with a period of 1.337s, was discovered nearly 40 years ago - by Jocelyn Bell Burnell and Anthony Hewish from Cambridge University in 1967. The two researchers were astounded at the unprecedented regularity and stability of the radio pulses they discovered coming from an unexplained source. For a time it was seriously thought that the observed signal was actually coming from an extraterrestrial civilization, and consideration was even given to destroying the observation data for the good of mankind. Indeed, that first pulsar, now known as PSR 1919+21, was then temporarily designated LGM-1 (Little Green Men 1).

Official confirmation of the signal's natural origin in February 1968 came as sensational news, and by the end of same year 100 publications had already been produced about this new type of object. New pulsars had also been discovered, including a famous one left behind by a supernova observed in the Crab Nebula

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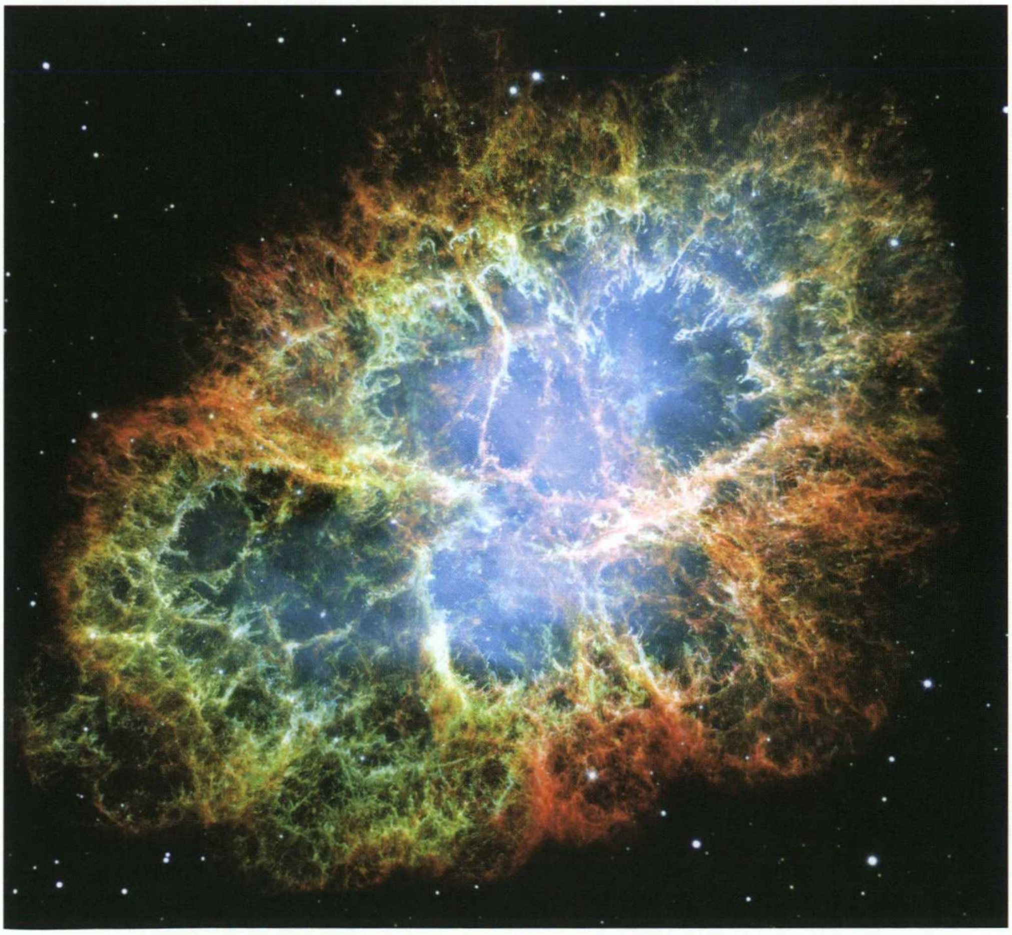


The Crab Nebula envelops the most famous of pulsars: the remains of a supernova whose explosion was observed on Earth back in 1054

in 1054. Initial doubts in understanding the pulsar mechanism were quickly resolved once it was demonstrated that the signal did not result from a binary system, from surface pulsations, or from the rotation of a white dwarf. The only sensible solution proved to be the notion that the observed pulses resulted from the rotation of an object much denser than a white dwarf, with a strong magnetic pole. In 1968, Pacini and Gold independently proposed the "lighthouse" model, i.e. a rotating magnetic dipole sending out radio waves.

Nowadays we know that the discovery of pulsars offered the first confirmation of the existence of neutron stars, predicted by theoreticians in the 1930s. Landau had posited a model of stars that were built from tightly packed atomic nuclei as early as in 1931 - actually one year prior to Chadwick's correct interpretation of the experimental data and discovery of the neutron itself! A typical neutron star results from the explosion of a supernova and has a mass similar to that of our Sun, but is several thousand times smaller in radius, i.e. about 10 km. Such extraordinary traits mean that the density of the matter in its center can repeatedly exceed the density of the atomic nucleus: these extraordinary stars are the densest material objects known to science, and in terms of relativistic effects such as the warping of time-space they are second only to black holes. Neutron stars likewise possess strong magnetic fields ($10^8<B<10^{15}$ G), at least tens of millions of times stronger than that of the Earth. These fields are crucial in generating the radio pulses we detect.

The discovery of pulsar PSR B1913+16 was crucial for the first-ever detection of gravitational waves

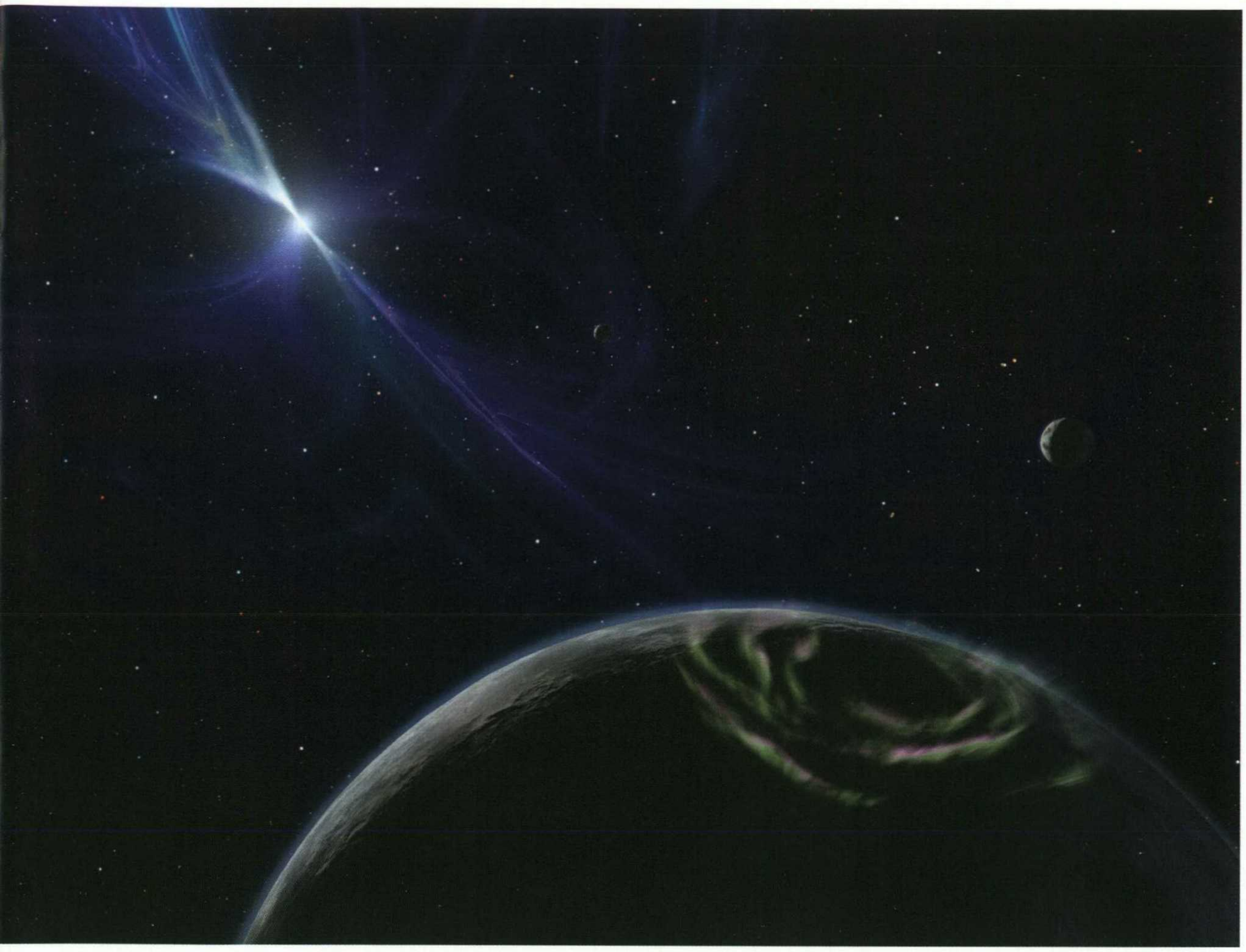
The information we obtain by observing pulsars is used to test theories about how this magnetosphere is structured and what processes occur in it, and also, indirectly, to draw conclusions about the inner structure of neutron stars. The basic parameter to be measured is the star's rotational period, or P. The 1,700 pulsars currently known have periods ranging from about 10 seconds down to a few milliseconds (the fastest "millisecond pulsar" now known rotates at a period of 1.4 ms, which means 716 rotations a second or a frequency of 716Hz). The interaction of the star's magnetic field with the surrounding matter means that a pulsar clock does not "tick" with absolutely uniform regularity - a gradual change in the rotational period can be observed, $P'=dP/dt$. For most pulsars $P'>0$, which means that a given pulsar is slowing down. For some pulsars the second derivative of the period, P'', is likewise measured. Studying changes in periodicity supplies us with important information about these superdense stars, enabling us to describe the complicated structure of their magnetic poles and the processes taking place around them.

Soon after the first pulsar was discovered, its periodicity was found to be extraordinarily stable (its value remaining constant down to 7 significant digits); the stability of millisecond pulsars is much greater, down to as many as 13 significant digits. Comparative experiments carried out by many research groups have shown that over long timeframes (of the order of years), millisecond pulsars are just as stable or sometimes even more stable than superaccurate atomic clocks on Earth, i.e. devices that harness the resonant frequencies of certain atomic energy transitions to define time units. This extraordinary property of the "pulsar mechanism" was used by the architects of the Pioneer 10 and 11 space probes - they outfitted each probe with engraved plates bearing information about our civilization, noting the position of the Solar System with reference to 14 nearby pulsars (changes in the rotational periods of these cosmic "navigation points" can be used to calculate when the probe was launched).

Explaining "glitches"

The pulsar mechanism is so precise and predictable that the observation of any irregularity in their "ticking" leads in most cases to breakthrough discoveries. Such an irregularity led Wolszczan and Frail, using the Arecibo telescope, to discover the first extrasolar planetary system. The system contains three planets (as well as perhaps comets) that signal their presence via the Doppler effect, i.e. by delaying or accelerating the arrival of individual pulses from the star they orbit.

By analyzing the arrival time of pulses from another pulsar, PSR B1913+16, located in a tight binary system alongside an invisible, dense companion, Hulse and Taylor correctly interpreted their periodicity changes as being a consequence of the General Theory of



An artist's impression of the planets orbiting pulsar PSR 1257+12, studied by Aleksander Wolszczan

Relativity: the advancement of the periastron (the line between the stars when closest to one another), the tightening of their orbits, time dilatation and gravitational red-shift are all direct consequences of the system's giving off energy in the form of gravitational waves. This discovery marked the first astrophysical detection of gravitational radiation and confirmed the correctness of Einstein's theory of gravity! Radio signals coming from binary systems containing neutron stars are also used to measure the masses of such stars, with an accuracy of many decimal places.

Pulsar chronometry helps researchers to unlock the hidden secrets inside neutron stars: in the case of young neutron stars, certain "glitches" can be observed, i.e. sudden occasional increases in rotation frequency amidst a general gradual slowdown. The "glitch" phenomenon can be explained by a model involving the transfer of the moment of inertia from the star's superliquid core to its crystalline crust. By studying the frequency distribution of glitches and positing theoretical models for them, researchers hope to gain better insight into the phenomena taking place within the dense, degenerate and superliquid matter inside the stars.

Analyzing pulsars' clock-like mechanism supplies us with ever-greater information about the physics of neutron stars' magnetospheres, masses, and internal structure, as well as about the theory of gravitation and gravitational wave radiation. We can be certain that further observations and theoretical work in this field will yield more discoveries and practical applications in the future. ■

Further reading:

Zdunik J.L., Bejger M., Haensel P., Gourgoulhon E. (2006). Phase transitions in rotating neutron stars cores: back bending, stability, corequakes and pulsar timing. *Astron Astrophys, 450*, 747-758.

http://science.nasa.gov/newhome/help/tutorials/pulsar.htm