ASTROPHYSICS

Weighing in on neutron stars

The more massive a neutron star is, the greater the constraints it places on the nature of the matter at its core. The discovery of a new mass record holder has strengthened those constraints considerably. SEE LETTER P.1081

M. COLEMAN MILLER

Large mass is a touchy subject among humans, but for neutron stars it is greatly desirable. This is because high mass places strong constraints on the matter in these stars' cores, which exists in a state that cannot be probed in laboratories and could be dominated by anything from neutrons and protons to exotica (such as quark matter that is not confined inside nuclei, hyperons or condensates). On page 1081 of this issue, Demorest *et al.*[1] report measurements of a neutron star with a mass nearly 20% greater than any previous, precisely measured value.

The object studied by Demorest and colleagues is a millisecond pulsar with a companion star. A millisecond pulsar is a rotating neutron star that emits a beam of radio waves at regular millisecond intervals. For this particular source, known from its sky coordinates as J1614–2230, the authors use a felicitous orientation of the binary system, along with the extreme timing stability characteristic of millisecond pulsars, to measure the 'Shapiro delay'. This delay, predicted in 1964 by Irwin Shapiro[2] using general relativity, occurs when light passes through the gravitational field of an object during its journey to Earth (Fig. 1).

As seen from a large distance, clocks run more slowly in deeper gravitational potentials. As a result, in a binary system this delay increases and decreases periodically with a characteristic shape and depth that depend, respectively, on the system's orbital inclination relative to our line of sight and the mass of the companion. When combined with classical measurements of the binary orbital period and of the line-of-sight speed of motion of the pulsar (as determined from Doppler timing shifts), the delay yields the masses of both the pulsar and its companion. The Shapiro delay has been measured before (for example, for the double pulsar J0737–3039; ref. 3), but never with enough accuracy to provide precise mass estimates without measurements of additional relativistic parameters.

Importantly, and unlike alternative post-Keplerian effects such as the precession of the orbital pericentre (the point at which the two masses are closest), the Shapiro delay does not depend on complicating effects such as tidal forces on the companion. It therefore provides a robust estimate of the masses. It

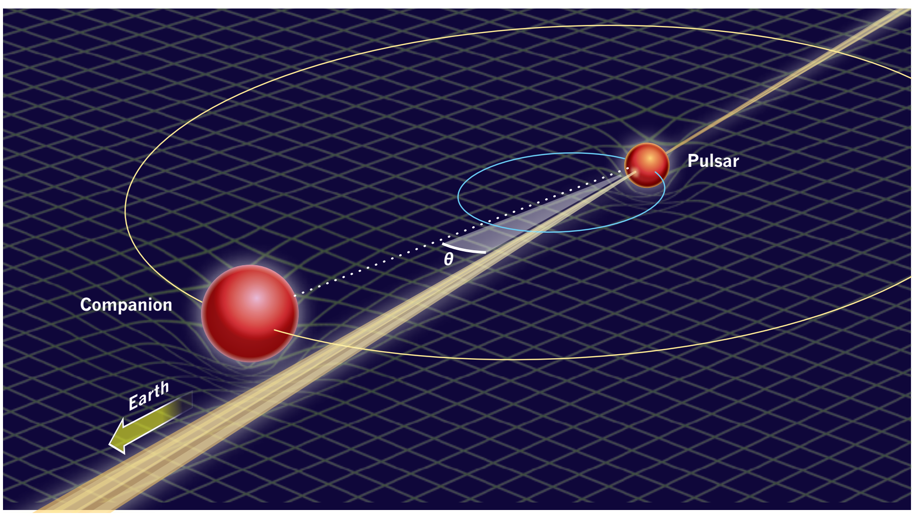

Figure 1 | The Shapiro delay. Radio waves from a pulsar that pass close to a companion are affected by time dilation through the companion's gravitational well. At a given moment, the resulting time delay due to a companion of gravitational mass M is $\Delta t = -(2GM/c^3)\ln(1 - \sin i \cos\theta)$, where G is Newton's constant, c is the speed of light, i is the inclination of the orbit to our line of sight, and θ is the instantaneous phase of the orbit. Nearly edge-on systems such as the binary pulsar J1614–2230 studied by Demorest *et al.*[1] produce comparatively large Shapiro delays during conjunction (where $\theta = 0$).

is, however, a weak effect, which is difficult to measure unless the binary system is nearly edge-on to us. In such a configuration, the radio waves from the pulsar pass very close to the companion at conjunction (the point at which the objects are nearest to each other on the sky), thus maximizing the signal. Indeed, J1614–2230 is the most edge-on binary millisecond pulsar known, with an orbital inclination of about 89.17°.

Demorest *et al.*[1] find that the neutron star in J1614–2230 has a gravitational mass (that is, the mass that would be measured by a distant satellite in orbit, in contrast to the approximately 20–30% larger 'baryonic mass' that would be obtained by summing the masses of all the object's constituent particles) of 1.97 ± 0.04 times the mass of the Sun. For comparison, before this, the highest precisely measured mass was 1.67 ± 0.01 times the mass of our Sun for the binary pulsar J1903+0327 (ref. 4), and the ultraprecisely measured masses of double neutron-star binaries span a range of only 1.25–1.44 times the mass of our Sun[5].

The reason that such masses matter to astrophysicists and nuclear physicists alike is that the matter in the cores of neutron stars exists in a regime that cannot be probed terrestrially, and nuclear theories on the composition and properties of this regime disagree strongly. Ordinary nuclei on Earth have densities of roughly 2.6×10^{14} times that of water. They also tend to have almost equal numbers of neutrons and protons. By contrast, neutron-star cores are thought to have densities that are about 2–10 times higher, and if they comprise primarily neutrons and protons then they have roughly ten times as many neutrons as protons.

In addition, other particles may dominate the interiors of neutron stars. The uncertainty principle of quantum mechanics says, among other things, that one cannot measure the position and momentum of a particle simultaneously and exactly. Thus, when neutrons are confined in a high-density region (and so the volume per particle is small and their positional uncertainty is low), they acquire a quantum-mechanical momentum, called the Fermi momentum, that can be substantial. The associated Fermi energy adds to the energetic cost per neutron; if other particles of lower total energy exist, they can substitute for neutrons. Hence hyperons and other exotica are a possibility in neutron-star cores, but there are enough uncertainties about, for example, their self-interactions that the ground state of high-density matter is not known.

One of the strongest discriminants between different models is the maximum observed mass among neutron stars. Models with exotica tend to have lower maximum masses than models dominated by neutrons and protons. This is because a transition to a lower-energy state at a high density makes the matter easier to compress and thus less resistant to gravity. In principle, modellers devoted to hyperons or quark matter can adjust free parameters to account for the mass of the neutron star in J1614–2230, but almost all existing models with such compositions are ruled out for a 1.97-solar-mass star (see ref. 6 for a recent review). Demorest and colleagues' results[1] are thus a vote in favour of neutrons and protons.

Even better, we may be seeing the dawn of an era in which Shapiro-delay measurements in pulsar binaries become more common and do not require remarkable chance alignments. The current limiting factor is the measurement precision of the arrival time of the radio waves. However, this precision is being improved rapidly thanks to its anticipated application in gravitational-wave detection by pulsar-timing arrays[7], which measure tiny shifts, induced by gravitational waves, in the arrival times of radio pulses from a collection of pulsars distributed on the sky. As a result, more and more systems will be open to such analysis, and we may see further evidence that heavy is beautiful. ■

M. Coleman Miller *is in the Department of Astronomy, University of Maryland, and the Joint Space Science Institute, College Park, Maryland 20742–2421, USA.*
e-mail: miller@astro.umd.edu

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STRUCTURAL BIOLOGY

A peep through anion channels

The crystal structure of a protein channel provides clues about the mechanisms that control the closure of pores found in the epidermis of plant leaves. Excitingly, the protein channel folds in a way never seen before. SEE ARTICLE P.1074

SÉBASTIEN THOMINE
& HÉLÈNE BARBIER-BRYGOO

You might think that bacteria have little to teach us about plants. But as Chen *et al.* reveal on page 1074 of this issue[1], you would be wrong. They report the three-dimensional structure of a protein from the bacterium *Haemophilus influenzae* that is structurally similar to the ion channel SLOW ANION CHANNEL 1 (SLAC1) found in plants, which is a key regulator of gas exchange between plants and the atmosphere. The structure reveals a previously unreported protein design that allows anions to permeate through membranes. By comparing the structure of the bacterial protein with a model of SLAC1, the authors were able to make selective mutations to the plant protein to investigate its activation mechanism.

The leaf epidermis of terrestrial plants contains pores known as stomata, which are formed by two kidney-shaped guard cells (Fig. 1). The pores' role is to control gas exchange between air spaces inside the leaves and the surrounding atmosphere. The influx of carbon dioxide through stomata determines the photosynthetic efficiency of the leaves, whereas the control of water-vapour efflux through the pores is central to maintaining water balance in plants. Drought, elevated carbon dioxide, ozone or pathogen attacks induce stomata to close[2], with the size of stomatal apertures being determined by the osmotic potential in the guard cells.

Stomatal closure is mediated by the release of ions from guard cells, a process that requires the coordinated efflux of anions and potassium ions accumulated inside those cells. The activation of anion channels is an essential step in stomatal closure, because it leads both to anion efflux and to the depolarization of cell membranes necessary to activate potassium-efflux channels. The membranes of stomatal guard cells harbour slowly activating anion channels (S-type channels), which display a strong preference for nitrate ions over chloride ions, and which allow sustained anion efflux upon activation by phosphorylation or calcium ions[2]. It has been proposed that S-type-channel activation is the key event leading to stomatal closure.

In the model plant species *Arabidopsis thaliana*, screens for mutants lacking stomatal responses to elevated carbon dioxide or ozone have identified mutations in the *SLAC1* gene[3]. *SLAC1* encodes a protein that has ten transmembrane α-helices, and whose amino-