



John Rowe Animations

I can't help falling in Love with Q

Neutron star insides are describable only using very complicated theories. But as **Matthew R Francis** reports, it now looks like the outsides of these objects may be fully defined by only three simple quantities, known as I, Q and Love

The dancers are an elegant pair. Clothed in the fabric of space-time, they are driven by the music of gravity and make a stately orbit around one another once every two-and-a-half hours. They pirouette as they move – one spins once every few seconds while the other spins many times per second – and each one of their twirls is marked by an intense flash of light. The dancing partners are pulsars – spinning neutron stars that send a regular blip of light our way.

Named PSR J0737-3039, this duo is one of a kind. More commonly known as the “double-pulsar system”, it is the only two-pulsar system where we have observed both partners. Other binary-pulsar systems exist, consisting of a pulsar and, for example, a white dwarf or a (non-radiative) neutron star. However, astronomers find the double-pulsar system particularly valuable because it consists of two flashing beacons rather than one, and the more information they

Matthew R Francis is a physicist and science writer. He blogs at <http://galileospendulum.org>, e-mail matthewfrancis@galileospendulum.org



Hope for I-Love-Q

The Green Bank Telescope in the US is one of the world's best instruments for studying pulsars.

can glean to test their theories, the better.

In particular, astronomers have yet to make a precise measurement of the size of any pulsar – they are too small to image using telescopes – and what pulsars are like on the inside remains a mystery. In the quest to figure out these details, what may prove vital is a fascinating discovery made in 2013: a set of simple relationships between quantities astronomers can measure, which bring clarity to the otherwise complicated theoretical landscape (*Science* **341** 365).

“You can use these universal relations to probe nuclear physics,” says Kent Yagi, an astrophysicist at Montana State University who co-discovered these relations. Yagi refers to how, by measuring and inferring certain values relating to the exterior of a pulsar – which is thought to be a simple solid crust – it is possible to probe the pulsar’s insides. In other words, we could finally discover what’s going on within the weirdest objects in the cosmos.

Three little words

Also known as neutron stars, pulsars are rapidly spinning objects that are the collapsed remnants of stars much more massive than the Sun; the most famous example is the Crab Nebula pulsar, born in a supernova explosion bright enough to be seen in daylight in AD 1054. They are as massive as stars, but are only 10–20 km across: smaller than many cities on Earth. Even our most powerful telescopes can’t measure neutron-star sizes directly, and the best estimates we have from X-ray telescope observations are only accurate to 50% or so. (That’s like saying my own height is between about 90 and 270 cm. Nobody’s happy with that sort of answer.)

Theoretical calculations don’t help much with figuring out their size, either. Pulsars combine strong gravity, intense magnetic fields and very dense nuclear matter; any one of those properties is complicated enough to study and understand, but together they are an astrophysics nightmare. “We don’t understand what a neutron star is made of,” says West Virginia University astronomer Maura McLaughlin. Not that we know *nothing* about these objects: “There must be neutrons in it. We know there’ll be electrons and protons. But aside from that

there are a whole bunch of different theories, many of which are plausible.”

Plausible isn’t good enough, especially since the different theories lead to different relationships between the mass of a neutron star – which astronomers can often measure – and its size. However, when a neutron star is a pulsar, it emits a strong beam of light. As the star rotates, one of its beams passes across our field of view, where we see it as regular flashes. The timing of these pulses and how they change led astronomers to conclude that the interior of a neutron star is a friction-free superfluid made of nuclear particles, while the surface is a solid crust of iron and other nuclei. That’s a nice broad picture, but we still need the details.

Yagi became interested in neutron stars through their gravitational properties. While the basic description of neutron stars in general relativity had been worked out years before, Yagi and collaborators realized there were new insights involving observable quantities. “Generally,” says Yagi, “we would expect that if we take two observables of a neutron star, the relations between those two observables would depend strongly on the internal structure that we don’t really know.” But he and his colleagues found the opposite: the space–time outside a pulsar can be described by three related quantities that depend on the object’s shape and size, rather than on any theoretical assumptions about the interior.

Yagi and collaborators coined the phrase “I-Love-Q” to describe the neutron star and the way it shapes space–time. Although this sounds like some bizarre romantic declaration, each “word” simply represents one of the three observables. “I” is the moment of inertia, which tells us how hard it is to change the rate at which an object spins. The classic example is a figure skater. When they begin a spin, their arms are extended and they have a large moment of inertia; if they pull their arms over their head, they decrease their moment of inertia and spin much faster. In other words, “I” depends on mass, size and how that mass is distributed within the body. A neutron star with a heavy core and light outer layers would have a lower “I” than one with the same mass distributed more evenly throughout the interior. Similarly, a large object will have a larger “I” than a compact body of the same mass.

“Love” refers to Love’s number, which shows how easy it is to squeeze a neutron star out of shape. High Love’s numbers indicate greater squishiness than low values. (Love’s number is named after the British mathematician Augustus Edward Hough Love, rather than the human emotion.) “Q”, meanwhile, is the quadrupole moment, which is a measure of how non-spherical the star is. A perfectly spherical neutron star would have a “Q” of zero, but if it were lumpy or egg-shaped, the number would be higher.

It’s easy to see how “Love” and “Q” are related: the squishier a neutron star is, the more likely it is to be non-spherical. Similarly, the connection between “I” and the other two quantities is logical. But Yagi and co-workers determined that not only are these quantities related, but they are the only ones we need to describe a neutron star exterior. Even though these

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numbers arise from the pulsar's interior, the I-Love-Q relationship is entirely independent of our knowledge of whatever bizarre nuclear physics is going on inside. To put it another way: I-Love-Q gives astronomers a theory-independent way of describing a neutron star. And the relationship between the numbers means that if we can measure two of them, we get the third free. *If* we can measure any of them, that is.

It all ends with Love

Measurement is where observational astronomers like McLaughlin come in. McLaughlin uses the Green Bank Telescope (GBT) in West Virginia, which is both the largest fully steerable telescope (at 100m in diameter) and one of the best instruments in the world for studying pulsars. She also uses data from the space-based Chandra X-ray Observatory, and looks forward to getting data from the newly upgraded Laser Interferometer Gravitational-wave Observatory (LIGO) in the US. Due to begin observations next month, the hope is that Advanced LIGO will detect gravitational waves – disturbances in space-time with a range of causes including pairs of neutron stars on a decaying orbit that will lead to their collision.

In fact, LIGO has already provided information on pulsars. “We know they’re pretty darn spherical,” says McLaughlin, “or else LIGO would have detected gravitational waves from them.” That’s because gravitational waves are emitted in proportion to the quadrupole moment, “Q”. Advanced LIGO will either measure “Q” for some pulsars, or else push down the limit even further of how non-spherical they can be.

But the GBT and the double-pulsar system PSR J0737-3039 carry McLaughlin’s fondest hope. “We think that within a few years, we may be able to measure the moment of inertia of the neutron star,” she says. Thanks to the gravitational dance, astronomers have measured the mass of both pulsars very precisely. With the moment of inertia, the quadrupole moment measured by Advanced LIGO and the I-Love-Q relations, McLaughlin and colleagues would be able to obtain the size and ultimately the Love’s number. As she says, “This would be *huge*.”

Yagi agrees. “If we can measure those quantities independently,” he says, “we can maybe tell which internal structure model is the correct model.” Those three little words “I Love Q” would be a lovely confluence of observation using light and gravitational waves with pure theory, all in the service of understanding some of the strangest, most beautiful dancers in the cosmos. ■



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