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A two decade long ballet of two stars reveals a rare twist

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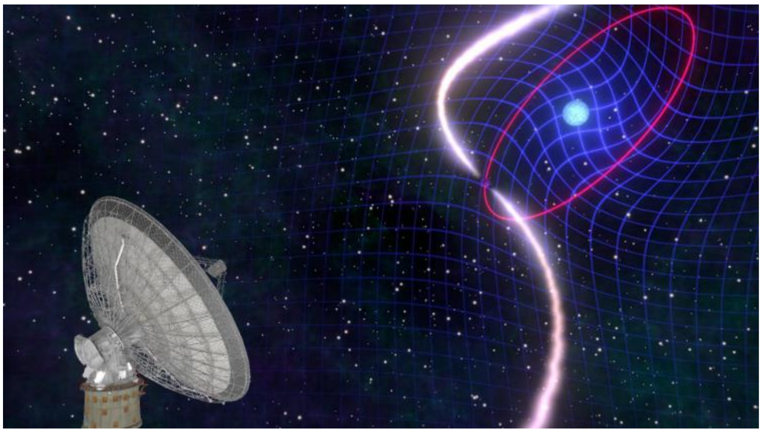
Einstein's theory of relativity predicts that rotating bodies twist the space-time around them. PSR J1141-6545 is a neutron star in orbit around a white dwarf star. Our two decade long observations reveal that its orbit is tumbling in space. This is, at least in part, due to the white dwarf's rotation twisting the space-time in its vicinity causing the neutron star's orbit to be dragged around.



https://youtu.be/GOb3MCAg9zM

Image credits: Mark Myers, ARC centre of excellence for gravitational wave discovery, Melbourne, Australia

General theory of relativity was arguably one of the most groundbreaking scientific advancements of the past century. According to the theory, gravity is not a mere force but a manifestation of the curvature of an underlying space-time fabric. Since its initial formulation in 1915, it has successfully withstood every test of its predictions, including the Nobel prize winning detection of gravitational waves from merging black holes in 2015.

One of the subtler predictions of the theory is that spinning bodies twist (drag) the space-time in their vicinity. This is known as "frame-dragging". Any spinning body, from spinning basketballs to spinning stars, drag space-time. However, frame-dragging due to everyday objects are inconsequential as their effects are immeasurably tiny. Even for an object as massive as the Earth, detecting frame-dragging required satellites equipped with high precision gyroscopes, and collection of almost a decade of data.

The strength of the frame-dragging is generally proportional to the spin frequency and the moment of inertia (the body's resistance against rotation). The best candidates to look at for this effect outside the solar system are stellar remnants (leftovers when a star runs out of fuel and sheds its outer layers or explodes into a supernova) such as white dwarfs, neutron stars and black holes.

Twenty years ago, the CSIRO Parkes radio telescope in Australia discovered a unique binary star system, nicknamed PSR J1141-6545. This system consists of a neutron star - visible to us as a pulsar - in orbit around a white dwarf star. A white dwarf is what is left over when stars similar to our Sun evolve and shed their outer layers. Such stars are roughly the same size as the Earth but a few hundred thousand times heavier (in this case, about 300,000). While that might seem grandiose, neutron stars are in another league altogether.

Neutron stars are the leftovers when stars that are about a few tens of the mass of the sun explode into a supernova. These are about 400,000 times heavier than the Earth but only the size of an average city. Such a dense environment makes all the protons and electrons in the core of the star fuse together to form neutrons. Neutron stars emit radio waves across their magnetic poles, which are seen as radio pulses due to the star's rotation. If the radiation is intercepted by the earth, these neutron stars are called pulsars.

As pulsars rotate, their radio beams appear as distinct pulses for every rotation, and we can use the arrival times of these pulses (that we record with very high precision using state-of-the-art atomic clocks) to map their orbit. This methodology, termed pulsar timing, has the ability to provide unparalleled measurements of pulsar properties. For example, even though PSR J1141-6545 is several hundred quadrillion kilometers away, we know the pulsar rotates 2.5387230404 times per second, and that its orbit is shrinking by about 2 mm everyday due to loss of energy.

The size of this binary orbit is so short that the stars orbit at velocities of up to a million km/h. Such high velocities, combined with the strong gravitational environment makes this system a rare laboratory for detection of several relativistic effects. After analyzing almost 2 decades of data from two different radio telescopes, we found that the whole orbit of PSR J1141-6545 was tumbling in space. After examining and ruling out several other reasons as to why this might happen, we realized that it should, at least in part, be due to the aforementioned frame-dragging effect caused by the rotation of the white dwarf star. This is the first detection of frame-dragging in a binary star system. Our measurements implied that the white dwarf is spinning rapidly, with a period that must be <15 minutes. This is much faster than the usual speeds of other known white dwarfs that are of the order of a few hours.

Contrary to most other known pulsar-white dwarf binaries, the white dwarf in this system is older than the pulsar. This is a very rare binary configuration as usually the supernova explosion that forms the pulsar also disrupts the binary orbit. The most promising theory on how this system came to be, postulates that sometime in its evolutionary history, the white dwarf accreted some matter from the pulsar's progenitor star (the star that exploded into a supernova and formed the pulsar). This process is expected to make the white dwarf rotate faster. Our measurements indeed show that the white dwarf must be rotating unusually fast, and hence is a confirmation of this evolutionary theory.