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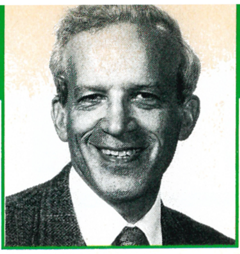


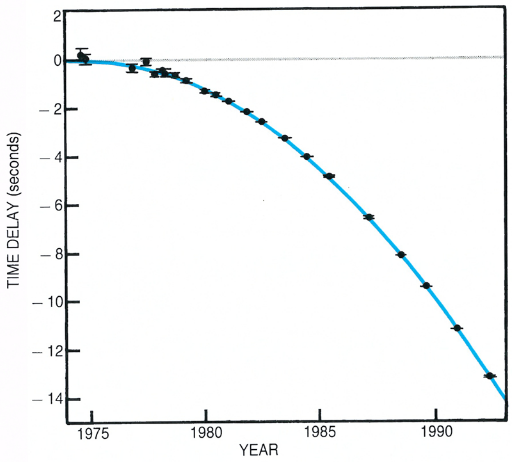
THE GEM OF GENERAL RELATIVITY

Daniel Kleppner

Once upon a time life was simple, science was small, and one could aspire to keep up with physics. Today keeping up requires more energy and time than most of us can muster. That, at any rate, is my excuse for not paying attention to general relativity as it blossomed from a curiosity into a hard science.

For 40 years general relativity was in the peculiar position of being the best known but the least verified theory in physics. The myth of general relativity was born in 1919 when Arthur Eddington announced to the world that he had observed the deflection of starlight by the Sun's gravitational field. Einstein became an instant celebrity, and general relativity was elevated to its mystical pedestal. The deflection of light, however, was barely discernible. There was one other strand of evidence—the precession of the perihelion of Mercury. But the precession rate was tiny and had to be extricated from effects of planetary perturbations. Theory does not flourish without experiment, and even as Broadway lyricists waxed poetic about general relativity ("Your charm is not that of Circe's with her swine / Your brain would never deflate the great Einstein"—Cole Porter), as did poets ("lenses extend unwish through curving wherewhen till unwish returns on its unself"—e. e. cummings), scientifically it remained little more than a curiosity.

Things started looking up for gravitational physics in the late 1950s. Robert Dicke created the field of experimental gravity by designing fiendishly sensitive tests of the equivalence principle and by devising tests for alternative gravitational theories. Robert Pound and Glen Rebka observed the gravitational redshift in the Earth's field. Joseph Weber started the quest to detect gravitational radiation. Irwin Shapiro, having realized that according to general relativity, gravity retards light, applied the newly created field of planetary radar to study it and carried out a generation of experiments on general relativistic effects using satellites, planets and stellar radio sources. Theory and experiment were in harmony, but the range of phenomena was narrow and the effects were small.



Delay in the time of periastron of the binary pulsar PSR 1913 + 16 as tracked over the years. The blue curve is the time delay due to the loss of energy by gravitational radiation; the curve is calculated from general relativity using the binary pulsar's measured properties, with no adjustable parameters. (Adapted from J. H. Taylor, in *Proc. IVth Rencontres de Blois*, T. Tranh, ed., IOP Publishing, Bristol, England, in press.)

In 1974 Nature suddenly started to flaunt general relativity. Joseph Taylor and Russell Hulse, working at the Arecibo radiotelescope, discovered PSR 1913 + 16, a binary radio pulsar that appears to have been exquisitely designed as a laboratory for general relativity. PSR 1913 + 16 is one partner in a pair of gravitationally bound masses, each approximately 1.4 times the mass of the Sun. These neutron stars rotate furiously around each other in an orbit not much bigger than the Sun's diameter, with a period of 8 hours. The pulsar constitutes a clock of fabulous precision that marks the time as it tears along its orbit. One could hardly ask for more.

The binary pulsar is no longer news. If you have kept abreast of the discoveries, its wonders may not amaze you. If you have not, read on.

Every 59 milliseconds the pulsar emits a "tick" that is so clear that the arrival time of a 5-minute string of these ticks can be resolved to within 15 microseconds. Clocking a signal for 18 years with a resolution of 15 μsec can give pretty high accuracy. To illustrate: The frequency of the pulsar is 16.940 539 184 253(1) Hz (the figure in parentheses is the uncertainty in the last digit), or at least it was on 14 January 1986. The frequency is changing slowly but steadily at the rate of $-2.475\,83(1)\times 10^{-15}$ Hz/sec. Considered simply as a clock, the pulsar is embarrassingly good. Apparently it is as accurate as the best atomic clock. Since atomic clocks are the most accurate devices science has created, it is evident that our clockmakers are up against stiff competition.

As the pulsar swings around its orbit, the pulse arrival rate increases and decreases owing to the Doppler shift, and the apparent pulsar time periodically advances and falls back. The amplitude of this variation is

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about 4 seconds. The delay curve is highly distorted because of the eccentricity and orientation of the orbit. By analyzing the shape of the curve and its evolution in time, Taylor and his colleagues have found out just about everything you might want to know about the orbit.

One needs five parameters to describe a Keplerian orbit. For PSR 1913 + 16 these parameters are now all known to an accuracy of 1 part per million or better. The eccentricity of the ellipse, for example, is 0.617 130 8(4). Another of the parameters describes the orientation of the major axis, or periastron, to use the euphonious astronomical term. As the periastron precesses, the phase of the distortion in the pulse arrival curve shifts with respect to the underlying periodic motion. From observing this shift over the years, Taylor and his colleagues have determined the precession rate with a remarkably low uncertainty.

To put that measurement in perspective, recall that according to general relativity Mercury's perihelion should precess at a rate of 43 seconds of arc per century. The binary pulsar, in contrast, precesses shamelessly at a rate 30 000 times larger. Taylor has measured the precession rate to be 4.226 62(1)° per year, a number so precise that even the most dyed-in-the-wool member of the Flat Earth Society would probably agree that the effect is real.

The measured precession rate agrees well with general relativity. Two neutron stars in the observed orbit, each with an expected mass close to the Chandrasekhar limit of about 1.4 solar masses, should precess at about 4° a year. By combining data on the precession rate, the orbital time dilation and the gravitational redshift, one can find the actual masses of the two stars. The result is 1.441 0(5) solar masses for the pulsar and 1.387 4(5) solar masses for the companion.

What makes the binary pulsar really sparkle, however, is its spectacular display of gravitational radiation. This evidence for gravitational radiation is a true "first" for general relativity, and it puts the pulsar in a class by itself.

The binary system pulsar is a rotating mass quadrupole, and it radiates gravitational energy. As in all bound two-body gravitational systems, the orbital period decreases as the energy decreases. To see the change, one simply keeps track of the total orbital angle swept out by the pulsar and watches how it departs from linearity with time. If the acceleration is uniform, the departure will be quadratic. (See the figure on page 9.)

It took Taylor and his colleagues a few years to notice that the orbital period was actually changing, and the first measurements were too crude to permit them to come to any conclusions. Two things helped. First, the technology for timing the pulses steadily improved. Second, lots of time passed. In measuring an effect that increases quadratically with time there is no substitute for watching and waiting, which is what Taylor has been doing for over 18 years.

To make a strong case for having seen gravitational radiation, however, you need to do more than accurately measure the damping rate. First, you must consider alternative mechanisms for changing the period. The binary pulsar doesn't seem to allow any. It is so close to an ideal two-body system that there appears to be no plausible scenario for its ejecting mass or otherwise changing its properties in a fashion that could account for the period change. Second, you must prove that the radiation rate agrees with the prediction of general relativity, given the measured masses and orbital parameters. For PSR 1913 + 16 the bottom line is that the ratio of the observed to the predicted damping rate is 1.0032 ± 0.0035.

Orbital precession and gravitational radiation are only part of the story, for the binary pulsar exudes relativistic phenomena. To mention just a few: The gravitational redshift from the varying potential of the pulsar is clearly visible, as is Shapiro's time delay. The gravitational redshift of the Earth–Moon system as it moves in the Sun's field is also visible. In fact, the timing measurements are so precise that the actual numbers become meaningful only when one specifies whether time is referred to an observer at the gravitational potential of the Earth, the solar system, the Galaxy or the cosmos. Because the binary pulsar is a gravitational radiator, it is also a gravitational absorber. If there were a background of gravitational radiation, the binary pulsar would show it. Little such radiation appears to be flying around. That implies, for instance, that the cosmological missing-mass problem is unlikely to be solved by mass–energy tucked away in gravitational radiation fields.

The binary pulsar was discovered in the course of a survey of radio pulsars. To a society that esteems short-term payoffs, if not instant gratification, astronomical surveys seem dull and tedious. It can be difficult to convince Congress and the public of the rewards that can flow from unglamorous research pursued patiently over the years. The history of the binary pulsar, however, makes a compelling case.

Taylor has studied PSR 1913 + 16 for almost 20 years, assisted by a few students, postdocs and collaborators, and working with modest instrumentation at the Arecibo facility. One could characterize this as small science at a big facility, and it is an example of small science at its best. In searching through the hundreds of pulsars, Taylor had the vision to notice that one was a gem of general relativity. One can only wonder what other gems are lying around, waiting for us to notice them.

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I thank Joseph Taylor for helpful discussions. ■