Gravitational Waves from an Orbiting Pulsar

Einstein's 1915 prediction that an accelerating mass should radiate energy in the form of gravitational waves is supported by evidence that a pulsar's orbit around a companion star is slowly shrinking

by Joel M. Weisberg, Joseph H. Taylor and Lee A. Fowler

Einstein's general theory of relativity, published in 1915, makes an extraordinary prediction: an accelerating mass should radiate energy in the form of gravitational waves. Yet the waves are so weak and their interaction with matter is so feeble that Einstein himself questioned whether they would ever be detected. In 1974, however, an object suitable for testing the prediction was found: the binary pulsar PSR 1913 + 16. The designation indicates that the radio-emitting pulsar and its radio-silent co-orbiting companion are positioned in astronomical sky charts at right ascension 19 hours 13 minutes and at declination +16 degrees, which places the binary pulsar in the constellation Aquila. In observations made with the largest optical telescopes no periodically blinking object can be seen at the pulsar's radio location. This is not surprising, because among more than 300 radio pulsars identified since the first was discovered in 1967 by Jocelyn Bell and Antony Hewish of the University of Cambridge only two are observable as visible pulsars.

Astronomers today generally agree that pulsars are very small, rapidly spinning, extremely dense stars, composed mostly of neutrons, that are the remnants of supernova explosions. These spinning neutron stars emit a highly directional radio beam that sweeps around the sky once per stellar rotation. An observer receives a pulse of radio waves each time the star's radio beam points at the earth, hence the name pulsar. A pulsar consists of approximately as much material as the sun yet has a diameter of only 20 to 30 kilometers because its atoms are literally crushed out of existence by intense gravitational forces. Pulsars are observed to be spinning at rates of up to 30 times per second. Some of this vast reservoir of rotational kinetic energy is converted (by a mechanism that remains obscure) into radio emission.

The binary pulsar is a unique tool for testing fundamental physical laws. Both the pulsar and its silent companion are more massive than the sun. They travel at velocities that range up to 400 kilometers per second in a tight orbit with a minimum separation about equal to the radius of the sun. These circumstances make the binary pulsar system an ideal laboratory for studies of strong gravitational fields. In particular the strong, gravitationally induced accelerations experienced by the pulsar and its companion should give rise to gravitational radiation. Until the discovery of the binary pulsar the best available gravitational laboratory was the solar system, where there is only one body of stellar mass (the sun) and where the nearest sizable object (Mercury) lies more than 65 solar radii away and is moving at an orbital velocity of less than 60 kilometers per second. Although there are other binary star systems in tight orbits, it is the presence of a pulsar in this particular system that makes possible a powerful test of gravitational phenomena.

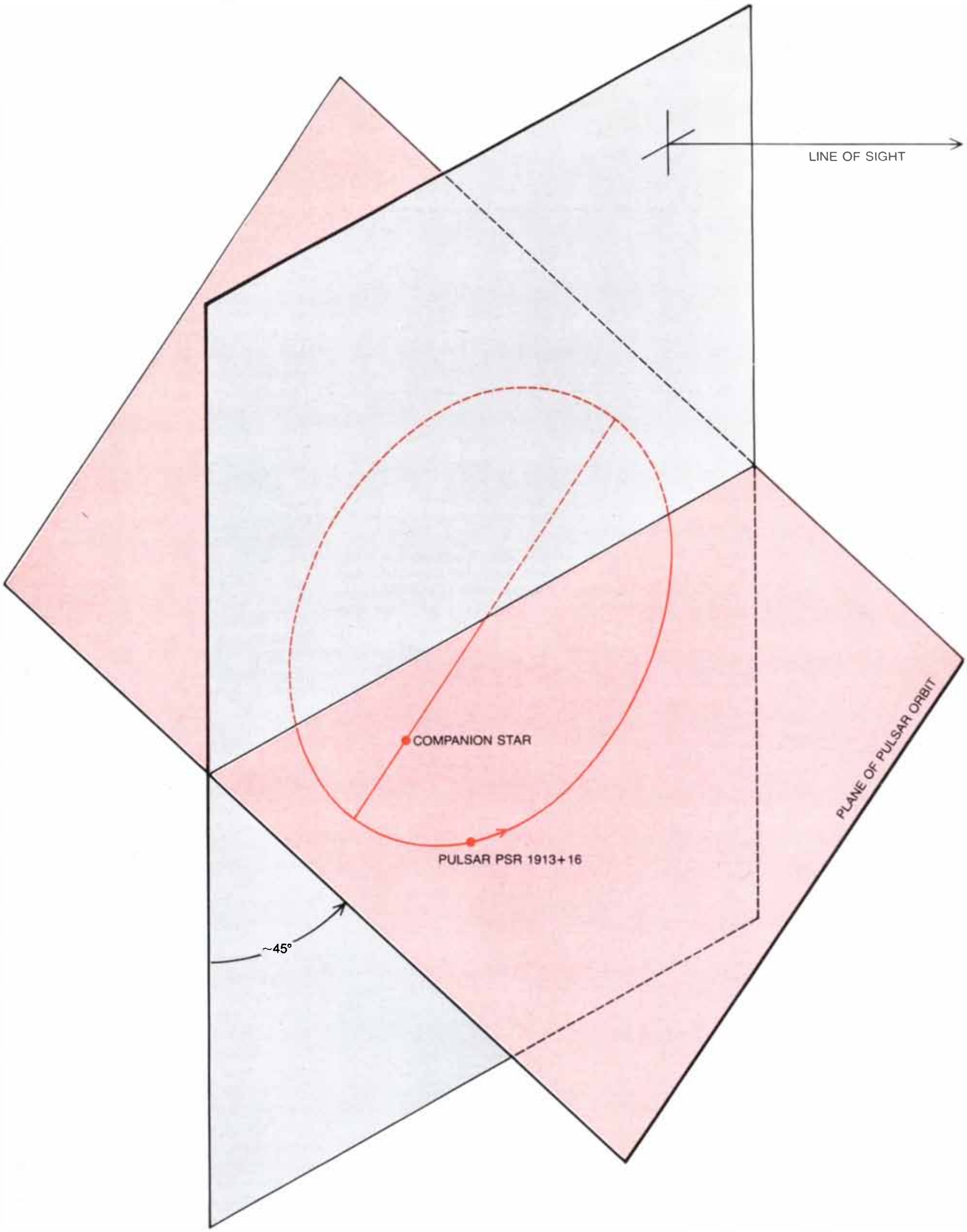
A pulsar is uniquely suited for the task because the pulse-repetition frequency (identical with the number of rotations the star makes each second) is so precisely stable that the pulsar's pulses are like the "ticks" of an extremely accurate clock. The pulse rate is stable because the pulsar acts as a massive, freely spinning flywheel that tends to rotate smoothly for an indefinite time. The binary pulsar is therefore a precise clock orbiting in the strong gravitational field of another massive body. By carefully measuring the times at which its pulses arrive at the earth one can use the pulsar clock to map the orbit and to probe subtle gravitational effects with an accuracy that is not possible in any other known system.

Our measurements of the pulses from PSR 1913 + 16, carried out over the past six years, show that the system is in fact losing orbital energy at a rate close to that expected from gravitational radiation according to the general theory of relativity. Our observations thus provide the first strong evidence for the existence of gravitational waves as well as further confirmation of the validity of general relativity.

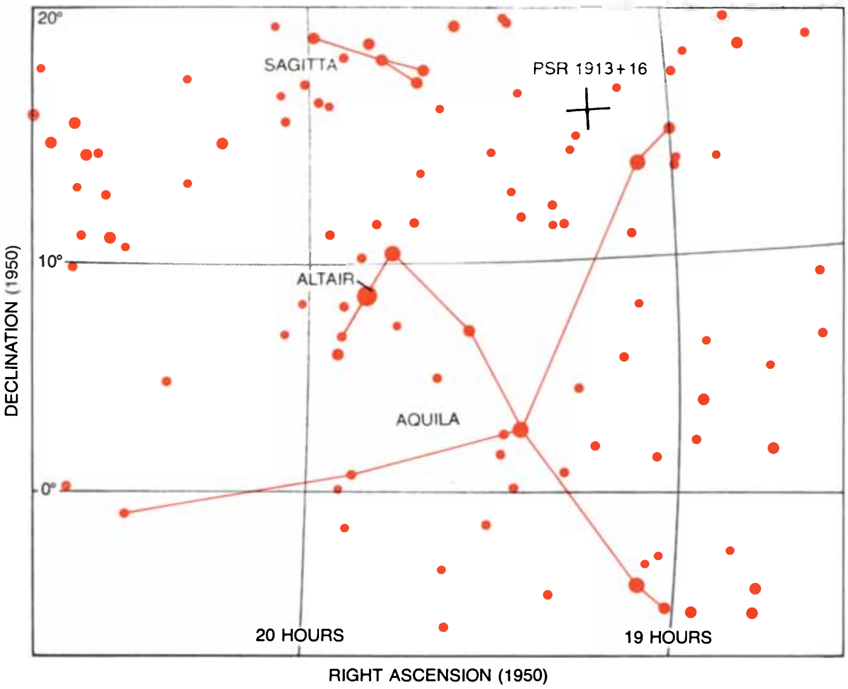
The laws of gravitation and motion developed by Isaac Newton more than 300 years ago have provided a remarkably accurate description of the motions of most orbiting objects. It has been known for many decades, however, that Newton's formulation begins to break down near very massive bodies. For example, there are slight irregularities in the orbital motion of Mercury that cannot easily be explained within the Newtonian framework.

The orbit of Mercury, like the orbit of all other planets, is an ellipse. The point on the ellipse where the planet passes nearest the sun is termed the perihelion. With the passage of time the perihelion advances, or rotates slowly in the same direction as the planet's direction of motion around the sun. Looking down on Mercury's orbit from above (that is, from above the planet's north pole), the advance of the perihelion is counterclockwise. There is a small discrepancy, amounting to only 43 seconds of arc per century (equivalent to less than twice the planet's diameter), between the advance in perihelion predicted by Newton's theory and the advance actually observed. This small anomaly was measured accurately even in the 19th century, before there was any theory to explain it.

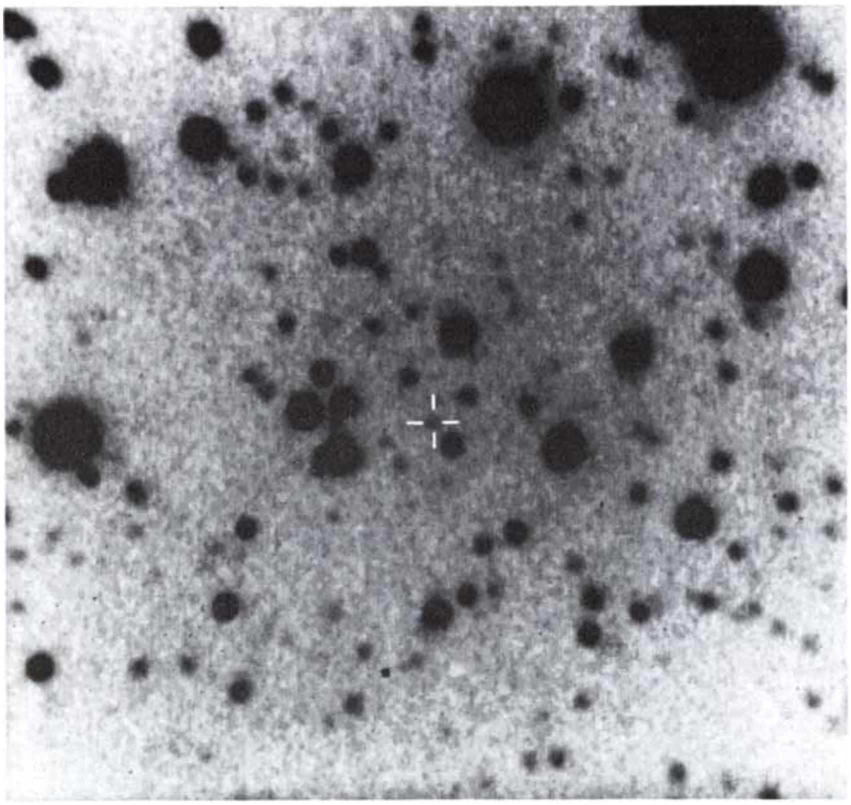
The cause is now generally ascribed to Mercury's being sufficiently close to the sun for Newtonian gravitational theory to begin to fail. The discrepancy is taken as strong evidence that the general theory of relativity is correct, since it predicts a perihelion advance of exactly the right magnitude. Nevertheless, a certain amount of controversy has continued, and attempts have been made to ascribe the discrepancy to other causes. For example, some physicists (most nota-



ORBIT OF PULSAR PSR 1913 + 16 lies in a plane tilted about 45 degrees from the line of sight. Like the more than 300 other pulsars discovered since 1967, PSR 1913 + 16 is thought to be a neutron star, 20 to 30 kilometers in diameter, that emits a radio beam that sweeps past the earth at precisely spaced intervals synchronized with the star's rate of spin. For PSR 1913 + 16 the spin rate is 16.94 revolutions per second. Unlike the large majority of other pulsars, PSR 1913 + 16 travels in an orbit around a companion star whose presence was inferred from a Doppler shift in the arrival time of the pulsar's "beeps." The beeps arrive slightly more frequently when the pulsar is traveling toward the earth and less frequently when the pulsar is receding. A complete picture of the pulsar's orbit around the center of mass of the binary system was derived through careful measurements of the Doppler shift in combination with an analysis of subtle gravitational effects predicted by the general theory of relativity. The theory made it possible to calculate that the pulsar and its companion are both 1.4 times as massive as the sun and that the separation of the two stars varies from 1.1 to 4.8 times the radius of the sun.



BINARY PULSAR PSR 1913 + 16 is in the constellation Aquila at the coordinates that supply its designation: right ascension 19 hours 13 minutes and declination +16 degrees. Its position is marked by the reticle. It is estimated that the binary pulsar is some 15,000 light-years away, too far for it to be observed optically even with the most powerful existing telescopes.



POSSIBLE SILENT COMPANION OF PSR 1913 + 16 is marked by a reticle in this computer plot of visible-light photons recorded with a video camera on the four-meter telescope of the Kitt Peak National Observatory. The observation was made by J. A. Tyson of Bell Laboratories. It has been suggested that the object is a helium-core star: a star near the end of its life that has ejected its outer layers into space, leaving behind a dense core consisting mostly of helium. If the companion is actually another neutron star, as the authors suspect, its visible radiation could not be detected by existing optical telescopes. In that case the object here would probably be a faint star that happens to lie at nearly the same position as the binary pulsar.

bly Robert H. Dicke of Princeton University) have suggested that if the sun were slightly oblate instead of perfectly spherical, at least part of the effect could be accounted for. The discovery of the binary pulsar was therefore particularly intriguing to those interested in fundamental physical laws, because the slight failure of Newtonian gravitation observed in the case of Mercury should be enormously magnified in a binary system where the orbiting bodies are both somewhat more massive than the sun and locked in close proximity.

In Einstein's general theory of relativity the Newtonian concepts of an absolutely definable space and an absolutely definable time are replaced by a single absolute quantity: space-time. Gravitational forces arise from local distortions of space-time caused by massive bodies. The trajectories of orbiting bodies are then seen as being merely the shortest paths that can be taken in warped space-time. Einstein himself showed that the advance of Mercury's perihelion is a natural consequence of the curvature of space-time in the vicinity of the sun. A related prediction of Einstein's theory, recently confirmed, is that radio signals traveling between the earth and a spacecraft on the far side of the sun should be slightly delayed as they pass close to the sun. A comparable time delay, again much magnified, could be expected if the two members of the binary pulsar system are oriented so that radio waves from the pulsar graze the silent companion body on their way to the earth. Therefore it is clear that the equations of general relativity are indispensable to a detailed analysis of the orbit of the binary pulsar. As we shall see, such analysis makes it possible to get much more information about the size and orientation of the orbit and the masses of the pulsar and its companion than could be got with Newtonian theory.

Most exciting of all was the opportunity presented by the binary pulsar system to verify a prediction of general relativity that had never been tested anywhere else in the universe: the prediction that accelerating masses (in this case the orbiting pulsar and its companion) should emit gravitational waves. Such waves, ripples in the curvature of space-time that travel at the speed of light, should be emitted by masses that are accelerating much as electromagnetic waves are emitted by electrically charged particles that are accelerating. The most sensitive laboratory techniques currently available are not nearly sensitive enough to directly demonstrate the existence of gravitational waves from the binary pulsar. According to general relativity, however, gravitational waves should carry a certain amount of energy away from the binary system. That energy should show up as a decrease in the system's orbital energy, resulting in a slight shrinkage in the size of the orbit and a corresponding decrease in the time required for the pulsar to circle its companion. It is this latter change that has now been measured, and with considerable accuracy.

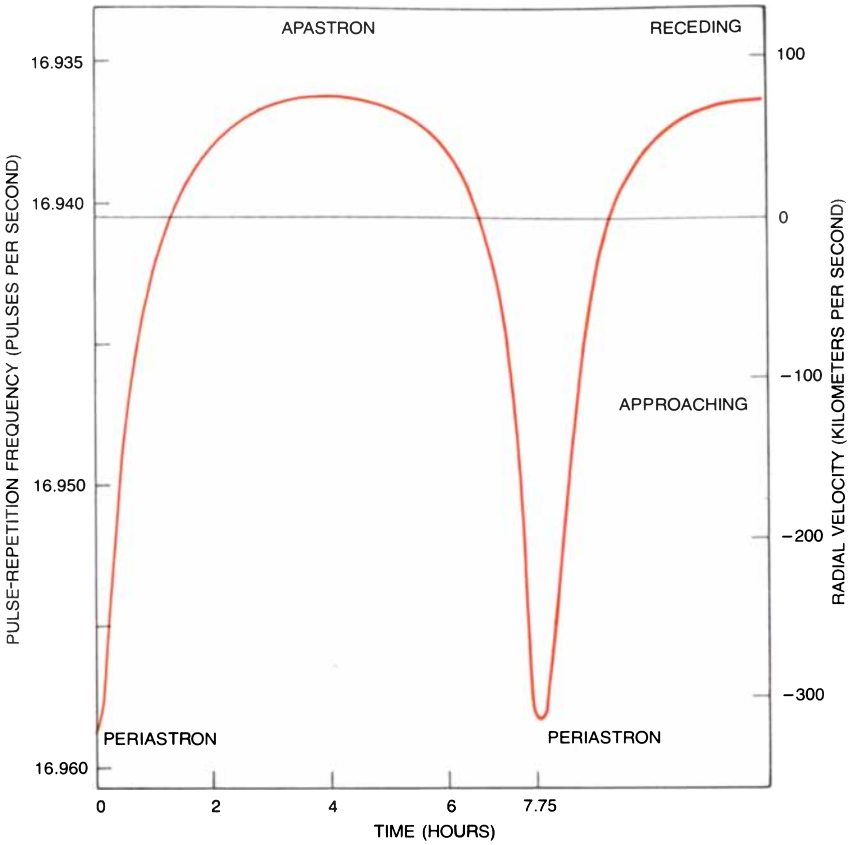
We shall now describe the binary pulsar system in some detail, beginning with the discovery of the pulsar and proceeding to the most recent measurements, which have made it possible to completely specify the orbital geometry and the masses of the two binary components, and also to test the general theory of relativity and other gravitational theories.

In 1974 Russell A. Hulse (then a graduate student at the University of Massachusetts at Amherst) and one of us (Taylor) began a search for new pulsars with the 1,000-foot radio telescope at Arecibo in Puerto Rico. Large areas of the sky were scanned for regularly pulsed signals. Since there are many terrestrial sources of radio noise (such as lightning, radar transmitters and automobile ignition systems) that can give rise to spurious pulsed signals, several procedures were devised to identify actual pulsars. The ultimate method of verification was to make subsequent observations of a candidate pulsar some days after an initial tentative discovery. If a pulsed signal with the same repetition frequency was detected on both days, the pulsar was accepted as real.

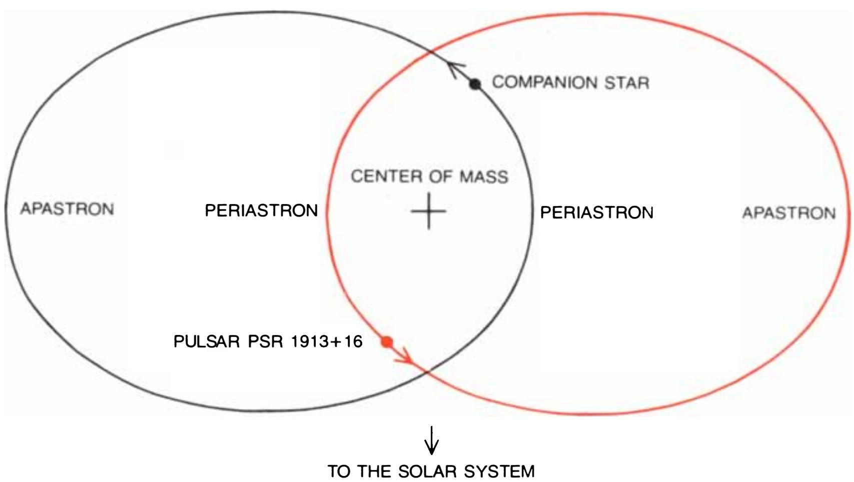
The Arecibo search revealed 40 new pulsars. Certainly the most remarkable was PSR 1913 + 16, whose pulse-repetition frequency was curiously not quite constant from day to day. After some detective work Hulse determined that the variation was cyclical, repeating itself every 7.75 hours. A natural explanation was that the pulsar was moving around another body in an orbit with a period of 7.75 hours. When the pulsar was traveling toward the earth in its orbit, the pulses were crowded together and the pulse-repetition frequency was slightly higher than the average 16.94 pulses per second; by the same token when the pulsar was receding from the earth, the pulse-repetition frequency was lower than average.

This behavior is simply a description of the well-known Doppler effect, where the observed frequency of any clock (including the regular waves of sound or light) is increased if the source and the observer approach each other and is decreased if they recede. The frequencies of the spectral lines observed in many binary stars exhibit a similar Doppler effect and for the same reason: orbital motion. Whereas the observable clock in a normal star of a binary pair consists of atoms in the star's atmosphere emitting or absorbing light of specific frequencies, the pulsar's clock is its rate of spin. In either case the same kind of information is obtained.

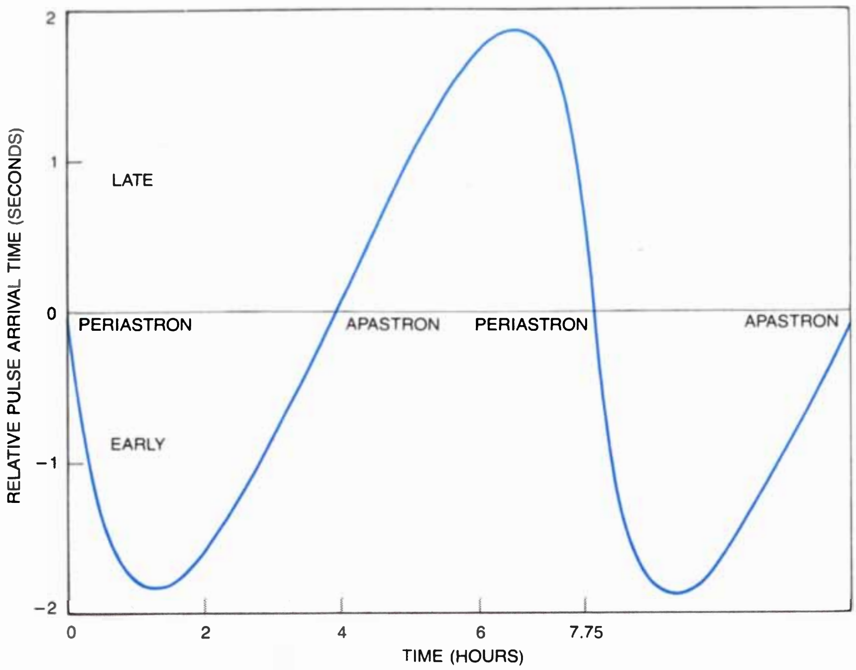
The standard techniques of binary-



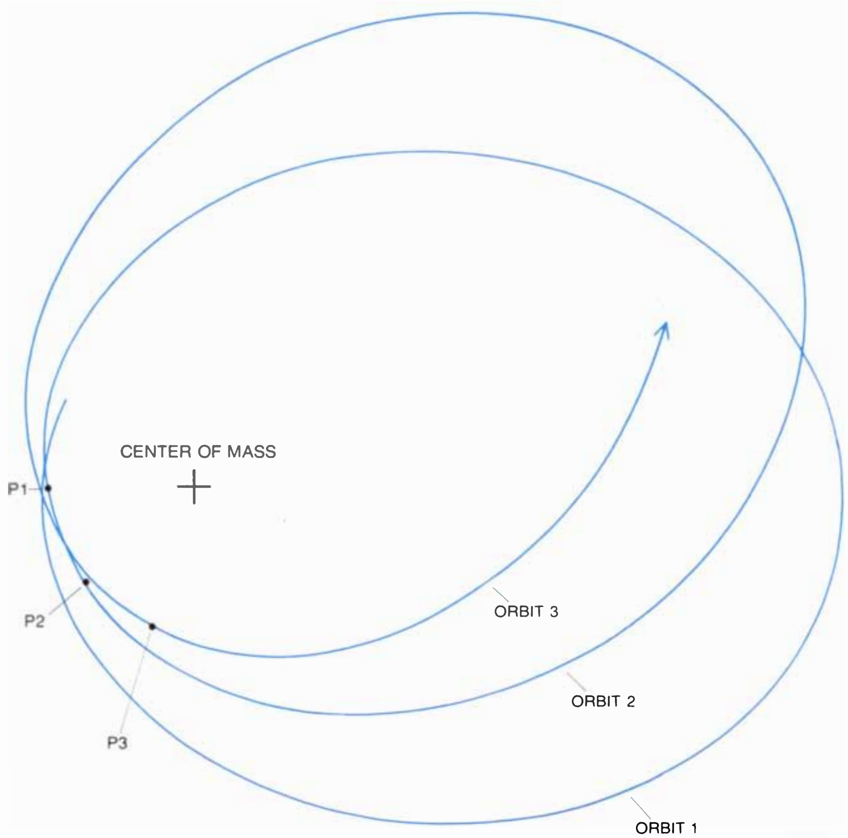
RADIAL VELOCITY OF PSR 1913 + 16 was calculated from changes in pulse-repetition frequency throughout the pulsar's orbital period of 7.75 hours by conventional Doppler-shift analysis. The frequency is lowest when the pulsar is moving away from the earth and is near apastron, the point where the co-orbiting bodies are farthest apart. The highest repetition frequency comes at periastron, when the bodies are closest together. The radial velocity is the component of the pulsar's velocity along the line of sight. Negative values indicate motion toward the earth. The existence of negative values larger than positive ones shows that the orbit is highly eccentric, with the pulsar gaining speed as it moves from apastron to periastron.



SHAPE OF THE PULSAR'S ORBIT, depicted in color, was determined from the radial-velocity curve. In this highly eccentric elliptical orbit the pulsar is about four times farther from its companion at apastron than it is at periastron. When the pulsar was discovered seven years ago, the major axis of its orbit was nearly perpendicular to the line of sight, as is shown here. Conventional Doppler analysis cannot determine several interesting parameters, such as the tilt of the orbital plane to the line of sight, the absolute size of the pulsar's orbit and the companion's orbit, and the masses of the two bodies. Knowledge of these parameters had to await an analysis on the basis of the general theory of relativity. The analysis revealed that the companion's orbit (*black ellipse*) is, to within an uncertainty of a few percent, the same size as the pulsar's. Major axis of the pulsar's orbit was found to be 4.5 times the radius of the sun.



TIME-DELAY CURVE depicts the variations in the arrival time of radio pulses from PSR 1913 + 16 as it travels in its orbit around its companion. When the pulsar is on the side of the orbit nearest the solar system, the pulses arrive more than three seconds earlier than they do when the pulsar is on the far side, indicating that the orbit is about a million kilometers across.



ADVANCE OF PERIASTRON in the orbit of PSR 1913 + 16 has provided one of the first clear observations of a general-relativistic effect involving bodies outside the solar system. The periastron advances, or rotates, as the elliptical orbit of PSR 1913 + 16 itself rotates in a plane because of the curvature of space-time in the vicinity of the pulsar's massive companion. In this diagram the effect is greatly exaggerated. The general theory of relativity predicts a periastron advance of about four degrees per year in the orbit of PSR 1913 + 16, the exact value depending on the total mass of the pulsar and its companion. The authors' measurements show the periastron is advancing 4.2 degrees per year, in good agreement with the prediction.

star analysis were therefore applied to the binary pulsar. The Doppler shifts were expressed as radial velocities (which are simply the components of the pulsar's orbital velocity that lie along the line of sight between the pulsar and the earth) and were plotted as a function of time. The radial velocity when the pulsar is approaching the earth, which is assigned a negative value, reaches a maximum of slightly more than 300 kilometers per second. The maximum radial velocity when the pulsar is receding from the earth is only about 75 kilometers per second. If the orbit were a perfect circle, the two extremes would be equal. Since they are not equal, one can conclude immediately that the orbit is highly elliptical and that the pulsar is approaching its companion and gaining speed in one segment of the ellipse and receding from its companion and losing speed in the opposite segment.

From the radial-velocity curve one can extract precise information such as the eccentricity of the orbital ellipse and its orientation in its plane. The calculations show that at apastron, the point of greatest separation, the two bodies are four times farther apart than they are at periastron, the point of closest approach. At the time of the initial observations periastron came near the time of maximum radial velocity when the pulsar was moving most directly toward the earth.

The standard method of radial-velocity analysis is not able to supply several interesting quantities such as the absolute size of the orbit, the tilt of the orbital plane with respect to the line of sight and the masses of the pulsar and its companion. For this information more accurate observations and a more sophisticated post-Newtonian analysis of the data were needed.

As a first step the absolute arrival times of pulsar pulses at the earth were carefully recorded; originally only the repetition frequency of the pulses had been measured. With this information the "phase" of the coherent train of pulses could be traced in addition to simply determining the pulse rate. The pulsar orbit could now be mapped more precisely than it could with the Doppler-shift data alone.

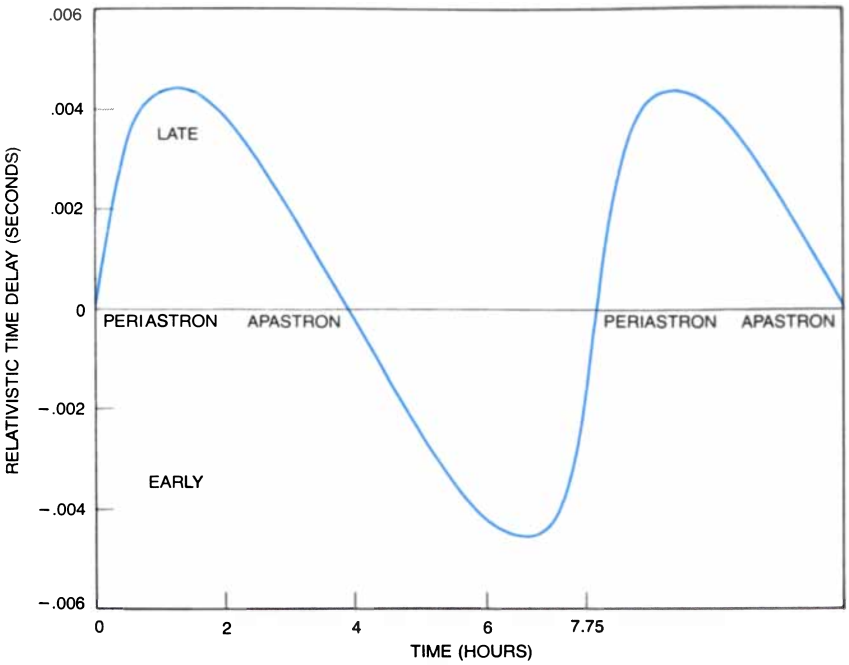
A plot of the time-delay curve, or variations in the arrival time of the pulses, shows that they arrive about three seconds earlier when the pulsar is on the near side of its orbit than they do when it is on the far side. Since radio waves travel at the speed of light (300,000 kilometers per second), the delay shows that the orbit is about a million kilometers in diameter. With the Arecibo telescope it is possible to measure the pulse arrival times to an accuracy of about 20 millionths of a second, thereby locating the pulsar in its orbit with a fractional accuracy of about one part in 150,000.

Let us now consider the subtler relativistic effects observable in the emission from the binary pulsar. The first measurable departure from Newtonian gravitation was an advance of the pulsar's periastron: a rotation in the orbital plane of the pulsar's point of closest approach to its companion analogous to the advance of the perihelion in Mercury's orbit. According to general relativity, the rotation should be about four degrees per year, an advance equivalent in one day to the advance of Mercury's perihelion in a century. There was some uncertainty because the magnitude of the effect depends on the masses of the pulsar and its companion, which were known only approximately at the time of the first calculation. Our first measured value of the advance of the periastron was 4.2 degrees per year. The success of this first attempt to utilize the binary pulsar as a gravitational laboratory encouraged us to carry out the other tests as well.

The next expected deviations from Newtonian theory have to do with the relativity of time. An observer's measurement of the time intervals marked by a moving clock depends on such factors as the velocity of the clock relative to the observer and the relative positions of the clock and the observer within a gravitational field. The orbital motion of the binary pulsar gives rise to two such phenomena: time dilation and the gravitational red shift. They combine to create an observable effect in the binary pulsar system known as the relativistic clock variation.

Time dilation is the apparent slowing of time measured on a clock that moves relative to the observer. Specifically, if an observer has two identical clocks and sends one of them off on a rocket moving at high speed while keeping the other clock with him, the rocket-borne clock will appear to measure the passage of less time than the stationary one. This idea is often expressed in the form of the "twin paradox": a man sent off on a spaceship traveling at nearly the speed of light discovers on his return that his twin who had remained on the earth has aged more than he has.

A clock running in a gravitational field of a given strength also appears to run slow when it is read by an observer in a weaker part of the field. This phenomenon is termed the gravitational red shift. The reality of these strange phenomena has been directly verified in a number of investigations. In one experiment Carroll O. Alley and his colleagues at the University of Maryland at College Park set up extremely accurate cesium-beam atomic clocks on aircraft and on the ground. After 15-hour flights the airborne clocks were found to be 47 billionths of a second ahead of the ground-based clocks. This result is in excellent agreement with the predictions of the general theory of relativity. According to the theory, the clock advance is explained by a combination of both kinds of relativistic clock variation: an advance of about 53 billionths of a second owing to the flying clocks' being in a weaker gravitational field because of their altitude (the gravitational red shift) and a retardation of about six billionths of a second owing to the airplane's speed (time dilation).



RELATIVISTIC CLOCK VARIATION has been observed in the arrival times of pulses from PSR 1913 + 16. According to the general theory, moving clocks and clocks in gravitational fields should appear to lose time when they are monitored by a distant stationary observer. The fourfold variation in the pulsar's orbital speed, combined with the highly elliptical orbit that carries the pulsar through a gravitational field with a strong gradient, provides a unique example of relativistic clock behavior. In accordance with the general theory the pulsar clock loses time while it is traveling fastest in the strongest part of the gravitational field of its companion. The maximum lag (compared with a hypothetical clock moving at constant speed and at constant distance from the companion) is a little more than .004 second. The pulsar clock then gains an equal amount as it travels more slowly in the weakest part of the field.

The speed of the binary pulsar varies by a factor of four as it moves in its elliptical orbit. The pulsar also passes through stronger and weaker regions of its companion's gravitational field as the distance between the two stars changes. As a result the observed pulse-repetition frequency of the pulsar clock varies from point to point in the pulsar's orbit owing to changes in both time dilation and the gravitational red shift. The two effects combine to advance or retard the pulses of the pulsar clock by as much as four thousandths of a second in different parts of the orbit.

As one can imagine, it is no easy task to distinguish the tiny relativistic variations in the pulsar clock from the much larger variations in pulse arrival time that result merely from the pulsar's changing distance from the earth. Nevertheless, in the time since the discovery of the pulsar its orbit has rotated sufficiently in its plane (owing to the relativistic advance of the periastron) to enable us to determine the magnitudes of the two kinds of variation separately. After six years of observations we have measured the amplitude of the relativistic clock variation to an accuracy of about 10 percent. As the orbital ellipse continues to change its orientation we expect to reduce the uncertainty in that measurement significantly.

The magnitude of the advance of the periastron and of the relativistic clock effects depends on the size and shape of the pulsar's orbit and on the masses of the two stars. Therefore by measuring these two relativistic effects we have obtained information that is useful in measuring the pulsar's orbit and in determining the total mass of the system. Indeed, the measurements of the two effects, along with the nonrelativistically determined orbital parameters, provide enough information to completely specify all the interesting orbital parameters as well as the masses of the pulsar and its companion. These calculations seem to be the first in which the general theory of relativity has been exploited as a tool for astrophysical measurement rather than simply a physical theory to be tested. We find that the orbital plane is tilted about 45 degrees from the line of sight, that the distance separating the two stars as they travel around each other varies from 1.1 to

4.8 times the radius of the sun and that both bodies have a mass about 1.4 times the mass of the sun.

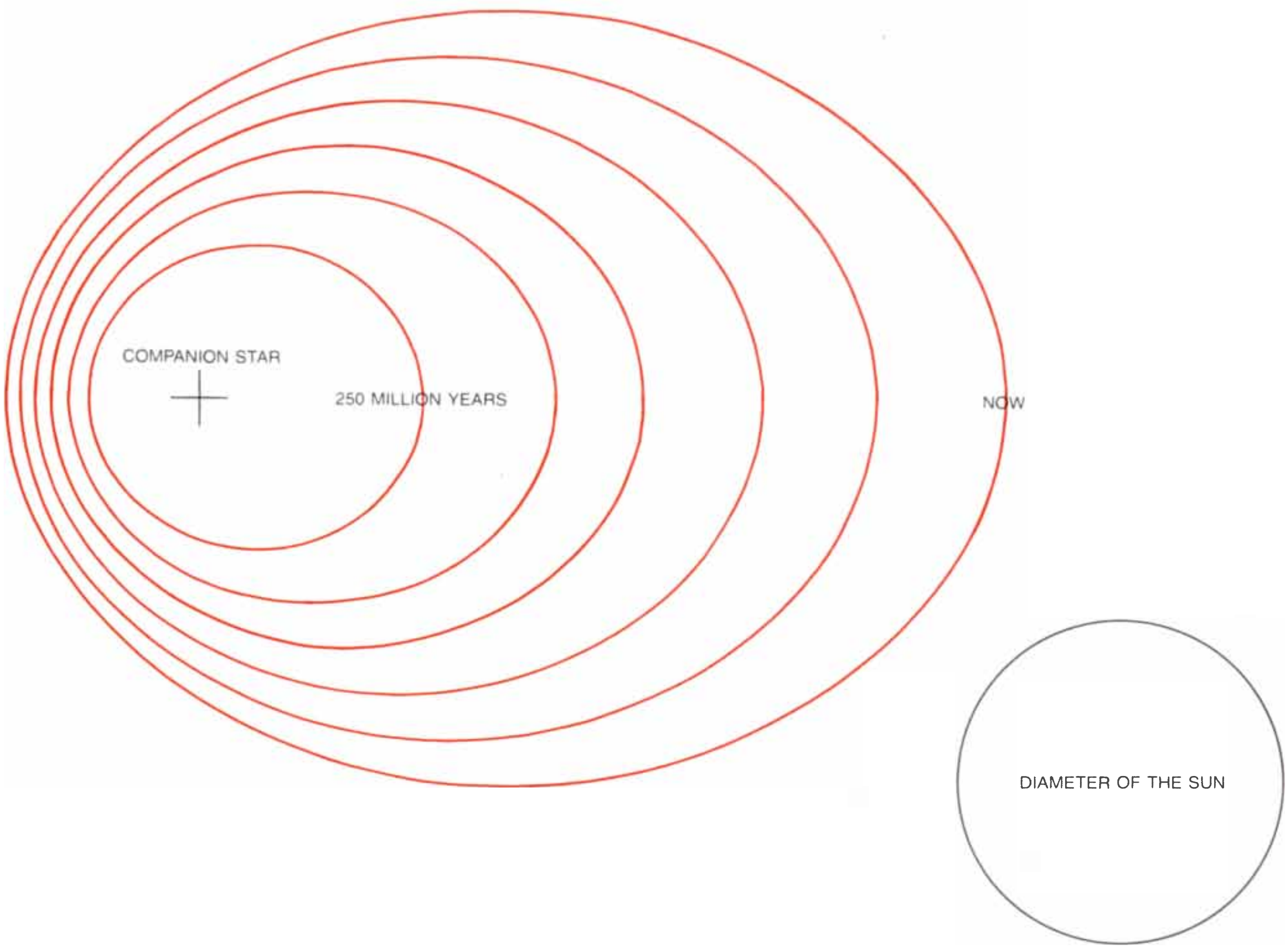
The binary pulsar is the first radio pulsar whose mass has been determined. The only ordinary stars whose masses have been measured are also members of multiple-star systems in which knowledge of gravitational laws can be combined with orbital measurements to yield mass values. The crucial difference, of course, between the mass measurements in the binary pulsar system and those in more typical binary star systems is that general relativity was invoked to provide some of the orbital information for the binary pulsar, whereas classical Newtonian laws suffice for ordinary binary stars. For example, measurements of the Doppler shifts of the spectral lines of two ordinary stars in orbit around each other (if both are visible) and observations of eclipses (for a system whose orbital plane is nearly edge on as it is seen from the earth) yield enough information to completely specify the orbital parameters and the masses of the stars.

The nature of the binary pulsar's silent companion can only be inferred; the object has not been observed directly. Our determinations of its mass and orbital parameters, however, coupled with stellar-evolution theory, have made possible some plausible guesses about its nature. The strongest constraint on the nature of the companion is that it must be small enough to fit inside the pulsar's orbit. This condition is satisfied by four known types of collapsed, dense stellar object.

The first and, according to stellar-evolution theory, most probable type of companion is another neutron star. Conceivably the companion is even another pulsar, one whose radio beacon does not happen to sweep across the earth. We shall return to this possibility when we describe a possible history of the binary system.

A second candidate is a black hole, a star whose gravitational collapse did not become stabilized at the dimensions of a neutron star but continued until all its matter was crushed to infinite density. It appears, however, that for a star to proceed to a state of unrestrained collapse at the end of its evolution it must be at least two or three times as massive as the sun. Since our calculations show that the companion has only about 1.4 times the mass of the sun, the companion is unlikely to be a black hole.

As a third possibility, the companion could be a white-dwarf star. Such an object is the remnant of a dying star, not more than 1.4 times as massive as the sun, that has collapsed to roughly the size of the earth. If the mass of the dying star is more than 1.4 times the mass of the sun, the collapse cannot be stabilized at the size of a white dwarf because the star's constituent atoms cannot resist being crushed by gravitational pressures to the next-smallest stable configuration, that of a neutron star. Since our estimate of the companion's mass is close to the instability point of 1.4 solar masses, a white dwarf cannot absolutely be ruled out, although present theories of stellar evolution indicate that it is unlikely for a system to form with a neutron star and a white dwarf

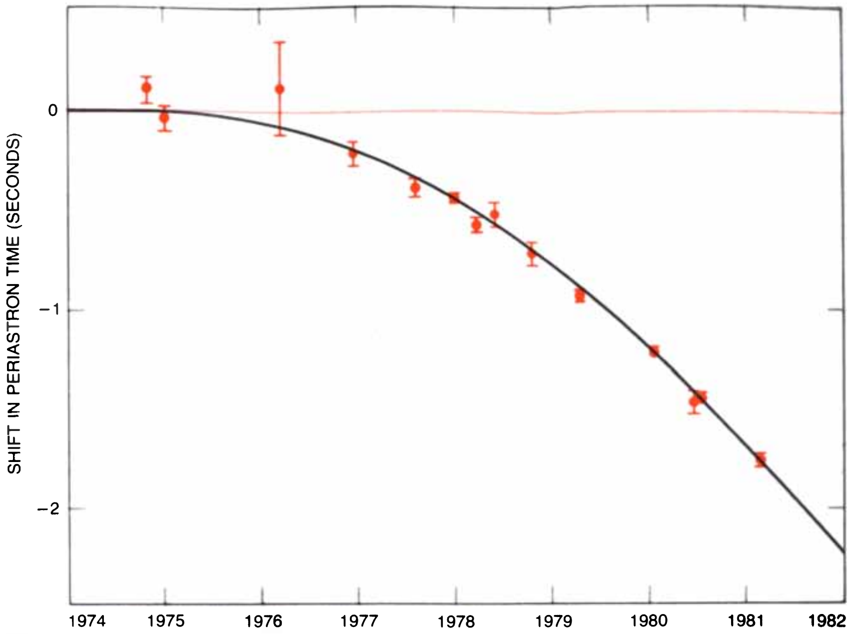


SHRINKING OF PULSAR'S ORBIT is projected on the basis of evidence that orbital energy is being converted into gravitational radiation, as is predicted by the general theory of relativity. According to the theory, the orbit of PSR 1913 + 16 should shrink by 3.1 millimeters per orbital revolution, or 3.5 meters per year. The orbital period should decrease accordingly by 6.7×10^{-8} second per orbit, or 7.6×10^{-5} second per year. This tiny change is measurable because it leads to a constantly accumulating deviation in the time of periastron passage. Here the orbit is drawn to scale as it will appear every 50 million years in the future until the two stars coalesce 300 million years from now. For comparison the sun is shown at the same scale. PSR 1913 + 16 is thought to be a 50,000th the diameter of the sun.

in such a tight orbital configuration. A white dwarf, like a neutron star, would be too faint to be observed with current optical telescopes at the estimated distance of the binary pulsar system: 15,000 light-years.

The fourth possible companion is a helium-core star. This rare kind of star consists of roughly one solar mass of matter compressed to a few tenths of a solar diameter. A helium-core star is the remnant, consisting mostly of helium, of a star that was originally much more massive. The helium, created by the thermonuclear fusion of hydrogen during the star's active lifetime, is left behind when the outer layers of the aging star expand tremendously and are either lost into space or are captured by the other member of a binary system. If the companion of the binary pulsar were a helium-core star, it might be visible with optical telescopes and might also give rise to measurable orbital effects. In fact, optical astronomers have recently detected a faint star close to the position of the binary pulsar that could be a helium-star companion. So far the only evidence linking the optical object with the binary pulsar system is the near coincidence in position. This coincidence may, of course, be accidental. Observations are continuing in an effort to clarify the nature of the optical object, which is near the limit of detectability for even the largest telescopes.

If the companion is indeed a helium star, its shape should be distorted by the pulsar's strong gravitational field. That distortion in turn could account for all or part of the observed advance in the pulsar's periastron, in the same way that an oblateness of the sun could theoretically account for part of the anomalous advance in the perihelion of Mercury. In addition the frictional energy loss associated with the distortion of a helium star might shorten the pulsar's orbital period, thereby mimicking the energy loss that we attribute to the emission of gravitational waves. Little is known, however, about the internal structure of helium stars, and estimates of the amount of change in orbital period that would be induced by a distorted helium star vary tremendously. It seems most unlikely that the dissipation of energy owing to a helium-star companion would just happen to equal the dissipation expected from gravitational radiation. We therefore consider it unlikely that the companion is a helium star.



EMISSION OF GRAVITATIONAL RADIATION BY PSR 1913 + 16 leads to an increasing deviation in the time of periastron passage compared with a hypothetical system whose orbital period remains constant. Solid curve corresponds to the deviation predicted by the general theory of relativity. Colored dots represent the deviation. The pulsar now reaches periastron more than a second earlier than it would if its period had remained constant since 1974. The data provide the strongest evidence now available for the existence of gravitational radiation.

Until 1979, PSR 1913 + 16 was the only binary pulsar known. Since then only two more binary pulsars have been discovered, so that such systems represent about 1 percent of the 330 pulsars now identified. It is estimated that approximately half of all the ordinary stars in our galaxy are members of binary systems (or systems consisting of more than two stars). Since pulsars are thought to represent a late stage in the evolution of ordinary stars in the range of masses from intermediate to large, one must explain why it is that roughly half of all pulsars are not found to be members of binary or other multiple-star systems. We shall first describe briefly what we consider a plausible history of the PSR 1913 + 16 system, one of the few systems that remained binary into the pulsar stage. Then we shall be able to comment on the general scarcity of binary pulsars.

We suggest that the system now observed as PSR 1913 + 16 began as a pair of ordinary stars, one star considerably more massive than the other and both together about 20 times as massive as the sun. The more massive of the two stars depleted its supply of nuclear fuel, chiefly hydrogen, much sooner than its companion did. With the depletion of fuel the outer layers of the more massive star expanded greatly and were captured by the less massive companion, leaving behind a helium-core star. After the star had consumed all its thermonuclear fuel it collapsed to an object a few tens of kilometers across and its outer layers rebounded in the tremendous explosion of a supernova. (The luminosity of such an explosion can rival that of the entire galaxy for a week or so.) Left behind as a remnant of the explosion was a spinning neutron star.

The companion star continued its evolution, eventually also expanding to the point where some of its matter was being pulled down onto the neutron star's surface, being heated in the process to temperatures so high that X rays were emitted. At that stage in the system's life it would have been observable as a binary X-ray pulsar, similar to those pulsars that have been observed by X-ray telescopes aboard artificial satellites in orbit around the earth. The outer layers of the companion continued to expand until they enveloped the neutron star. The friction of the neutron star plowing through the extended atmosphere of the companion was so great that orbital energy was rapidly dissipated and the orbit shrank drastically. As the companion's outer layers were heated by friction they were driven off into space, leaving behind a neutron star and a helium-core star circling each other in a very tight orbit. Finally the helium-core star exploded as a second supernova, leaving as a remnant a second neutron star.

We now observe one neutron star as a pulsar. The other neutron star may or may not emit radio waves; if it does, they apparently are not directed toward the solar system. The present highly eccentric orbit is evidence that the second explosion almost disrupted the system. Apparently most normal multiple-star systems are blown apart when one member explodes as a supernova, which explains the scarcity of pulsars in binary systems.

Let us now describe more fully the observational evidence that PSR 1913 + 16 is emitting gravitational radiation: the previously untestable prediction about accelerating masses made by

FIVE THOUSAND CONSECUTIVE PULSES from the pulsar are added together every five minutes, yielding a pulse profile such as the one shown here. The absolute time of arrival of the pulses at the Arecibo Ionospheric Observatory in Puerto Rico can be measured from the profile with an accuracy of 20 millionths of a second. The double peak suggests that the pulsar beam is a hollow cone; the peaks could be the two sides of the cone sweeping past the earth.

Einstein's general theory of relativity. Although gravitational radiation from the binary pulsar system is far too weak to be detected directly with present technology, the phenomenon should nonetheless be detectable indirectly.

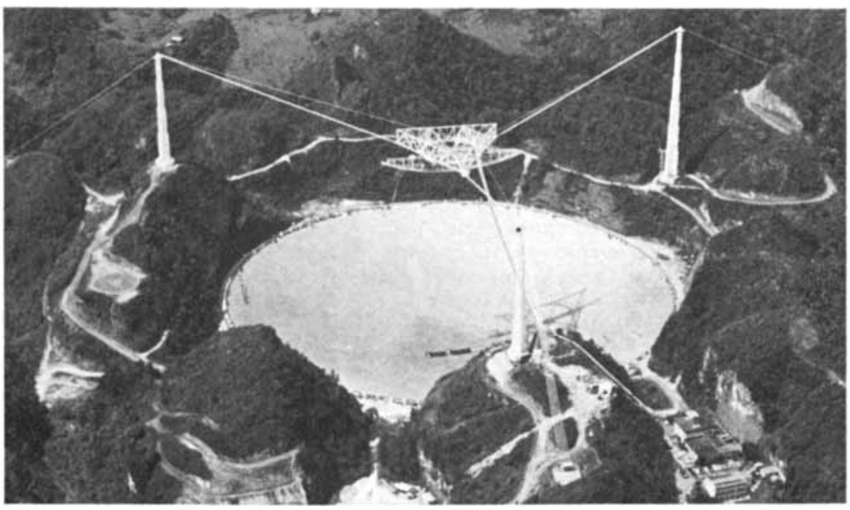
The source of energy for gravitational radiation from the binary pulsar is the energy of orbital motion. Therefore if gravitational waves exist and carry energy away from the binary system, the orbital energy should gradually decrease, causing the pulsar and its companion to spiral closer to each other and the orbital period to decrease. The orbit of an artificial earth satellite decays in the same way, although the satellite loses orbital energy not through the emission of gravitational radiation but through collisions with molecules in the upper atmosphere. (Strictly speaking, the satellite must also emit gravitational radiation, but it does so in negligible amounts.)

With our knowledge of the masses and orbital parameters of the binary pulsar system we can draw on the equations of general relativity to calculate the exact strength of expected gravitational radiation and hence the precise rate of contraction of the orbit and the decrease in the orbital period. We find that on each orbit the orbit should shrink by 3.1 millimeters and the orbital period should decrease by 6.7×10^{-8} second. There is no possibility of detecting the orbital shrinkage, amounting to 3.5 meters per year, even if the pulsar and its companion were as close to the earth as the sun and Mercury are and as readily observed. We can, however, measure the decrease in orbital period because it leads to an accumulating shift in the time of periastron passage compared with a hypothetical system whose orbital period remains constant. At the end of a year the pulsar should arrive at periastron .04 second early, and after six years it should arrive more than a second early. Thus the pulsar behaves like a poorly regulated clock that at first displays the correct time but begins to gain and then continues to do so at an ever faster rate. The cumulative error builds up quite rapidly: for the binary pulsar the shift should accumulate in proportion to the square of the elapsed time interval.

After six years of measurements we have found that the binary pulsar is indeed "gaining" in its orbit and that the acceleration is proceeding at almost precisely the rate predicted by general relativity [*see illustration on preceding page*]. This observation provides the strongest evidence now available for the existence of gravitational radiation. Moreover, the rate of decrease in the orbital period is not consistent with the predictions of several other modern gravitational theories that have been put forward as alternatives to Einstein's theory. We believe these alternative theories must now be rejected.

Hence 66 years after Einstein predicted the existence of gravitational waves an experiment has been done that yields clear evidence for their existence. Although the waves themselves remain elusive and undetected, their signature is plainly written in the orbital behavior of PSR 1913 + 16. A number of laboratory experiments designed to detect extraterrestrial gravitational waves are now in progress or being prepared, but even the best of them are not nearly sensitive enough to detect the waves from the binary pulsar. The experimenters seek instead to observe such cataclysmic (and rare) astronomical events as supernova explosions and the presumed formation of black holes.

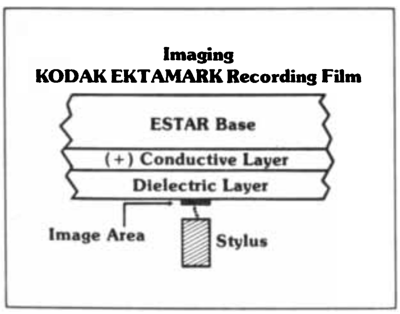
The reason for the difficulty of directly observing gravitational waves is straightforward: the interaction between the waves and any detector is so weak that it is overwhelmed by many possible contaminating effects, not least the unavoidable thermal motions of the atoms of the detector. Nevertheless, the binary-pulsar experiment should encourage the investigators who are developing gravitational-wave experiments. It now seems assured that what they are looking for does in fact exist.



INSTRUMENT USED IN DISCOVERY OF PSR 1913 + 16 is the 1,000-foot radio telescope at Arecibo. The pulsar system was found in 1974 in a survey conducted by Russell A. Hulse, then a graduate student at the University of Massachusetts at Amherst, and one of the authors (Taylor). The survey also turned up 39 other pulsars, none of them a binary. Of the 300-odd pulsars observed since the first one was discovered in 1967 only three are in binary systems.

Nice film without silver

Silver had better be saved for such ornaments of high civilization as elegant teaspoons, radiography of fractures, and the amplification of a light photon's kick by 10^9.



When energy with which to write in tiny dots can be supplied like this, you don't need that kind of amplification. Estar base is nicer than paper for carrying the conductive layer and the dielectric layer that receives the toner to visualize the electrostatic image. (No light sensitivity, no chemicals.)

In the great hunt for formations likely still to be holding hydrocarbon treasure, the geophysical industry's plotters have been drawing pictures something like the young lady is holding, but on dielectric recording paper. Paper gets pretty conductive when the humidity is up. That makes it hard to hold a fine-structured, crisp, electrostatic image. Estar base doesn't have that problem. And the film is quite transparent, not just translucent. Therefore that fine detail can be reproduced in the diazo machine without the services of somebody's copy camera.

On the chance that there are instrument people quite outside the geophysical industry who haven't heard about Kodak Ektamark recording film SO-222 and are feeling some excitement, Arnold Sullivan of our Graphics Markets Division is standing by with a fresh supply of exposed film. To obtain your samples, drop him a note at Kodak, Dept. GB-014, 343 State Street, Rochester, New York 14650.

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