

consulting with each other to determine which molecular ions are particularly worthy of attention. Once the Argonne group determines the structure to 0.01 Å in bond length, that narrows the frequency range in which Woods's group would need to scan. The Wisconsin equipment is capable of measuring frequency to eight significant figures, yielding bond lengths to better than 0.001 Å. The precision of the bond-length determination is at present limited by the theoretical treatment of molecular vibrations. —GBL

Gravity waves slow binary pulsar

Although most physicists have long been convinced that gravity waves would ultimately be detected, there has yet been no unambiguous experimental confirmation of their existence. Recent work by Joseph Taylor and Lee Fowler of the University of Massachusetts at Amherst and Peter McCulloch of the University of Tasmania, however, provides further evidence for the reality of these elusive waves. In the 8 February issue of *Nature* (277, page 437), Taylor, Fowler and McCulloch report that the orbital period of the only known binary pulsar is diminishing at a rate of about 3 parts in 10^{12} , which is consistent with quadrupole radiation of gravity waves by the system.

The data that have led to this conclusion come from four years of observation of the radio pulsar PSR 1913 + 16 with the 305-m radio telescope at Arecibo. The period of the pulsar is about a twentieth of a second and is known to a few parts in 10^{10} . To obtain the precise arrival times of the pulses, Taylor's group fits the long-term average pulse-profile to the sums of about 5000 pulses whose period has already been corrected for the Earth's motion. The position of some standard feature of the fitted profile then serves to define the arrival times of the pulses during a roughly ten-minute interval. Over the past several years the group has improved their equipment and analysis so that the uncertainty of their measured arrival times is now only about 50 microseconds.

As is the case for other pulsars, the arrival times are known precisely enough to be sensitive to even subtle effects from the motion of the Earth, including the annual change in the gravitational redshift as the Earth moves closer to and farther from the Sun. By obtaining data at two radio frequencies, the group can also correct for the dispersive delay due to the interstellar medium. The result of these corrections gives, in effect, the pulse period that would be seen by a stationary observer near the two orbiting stars.

The pulsar is in orbit around another star, which has not yet been directly ob-

References

1. Z. Vager, D. S. Gemmell, *Phys. Rev. Lett.* **37**, 1352 (1976).
2. R. Laubert, I. A. Sellin, C. R. Vane, M. Suter, S. B. Elston, G. D. Alton, R. S. Thoe, *Phys. Rev. Lett.* **41**, 712 (1978).
3. J.-C. Poizat, J. Remillieux, *Phys. Lett.* **34A**, 53 (1971).
4. M. J. Gaillard, D. S. Gemmell, G. Goldring, I. Levine, W. J. Pietsch, J.-C. Poizat, A. J. Ratkowski, J. Remillieux, Z. Vager, B. J. Zabranski, *Phys. Rev.* **A17**, 1797 (1978).
5. D. S. Gemmell, E. P. Kanter, W. J. Pietsch, *Chem. Phys. Lett.* **55**, 331 (1978).

served. This orbital motion, of course, affects the measured period of the pulsar, and the data are now numerous and precise enough to permit determination of the important orbit parameters. The orbit is a highly eccentric one, with a period of almost eight hours; its plane appears to be inclined at about 30° to the line of sight. The various parameters of the binary system can become disentangled because they affect the observed pulsar period with different functional forms and to different orders of v/c .

Two parameters are of particular interest for tests of general relativity: the rate of periastron advance, that is, the rate with which the orbit precesses, and the rate with which the orbital period decreases. The former is analogous to—but much larger than—the well-known perihelion shift of Mercury, which has provided one of the classic tests of general relativistic dynamics. The latter is the term providing evidence for gravitational radiation. The magnitude of the effect found by Taylor and his collaborators is consistent with the conventional general-relativity calculation for quadrupole radiation from two orbiting point masses, Taylor told us.

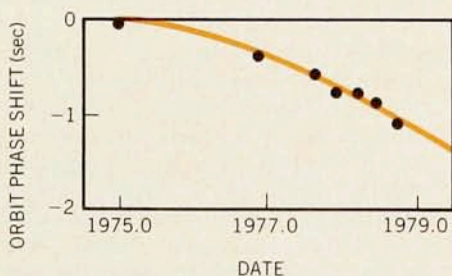
The only parameters of the orbiting stars that are not determined with great precision by the data are the masses of the stars. However, the formulas for several of the parameters used to describe the binary system do include the masses, and

the measured values of these give masses near $1.4 M_{\odot}$ for both objects.

The interpretation of the data depends somewhat on the model one assumes for the two stars involved. The most probable situation, Taylor told us, is that these are two compact objects in orbit around each other, behaving almost like ideal point masses. The mass of each object is in the right range for neutron stars, although other possibilities, such as white dwarfs are not ruled out. In either case, as Malvin Ruderman (Columbia) told us, it seems unlikely that tidal or similar effects are important: Even if the companion is a white dwarf, it must be so compact that it would behave as a rigid body. Mechanisms other than gravitational radiation, such as tidal or magnetic effects, would presumably also affect the pulsar period itself; unlike other fast pulsars, however, PSR 1913 + 16 is slowing down only very slowly (less than one part in 10^{17}). A number of noted astrophysicists have said that the observed effect could, in principle, also be due to a Doppler shift if the binary star were in a slow orbit around a distant third companion. However, Taylor remarked that Nature would have to be perverse to have given the third object just the right mass and distance to produce the observed decrease in orbital period. He added that data gathered over the next few years should enable his group to distinguish between such orbital motion and gravity-wave damping.

The figure shows the phase of the orbital motion with respect to the initial (1975) observation. Each point represents an average of several weeks' or months' data. The theoretical curve is the prediction from general relativity assuming both stars have masses of $1.41 M_{\odot}$. The important aspect is the apparent curvature; the mean slope of the points and of the theoretical curve indicate only the error in the value of the orbital period that was deduced from the initial observations. To confirm the fit, Taylor's group also computed the range of possible masses of the stars by fitting all orbit parameters except the periastron advance, but including the orbital-period decrease. This fit gave masses for the pulsar and its companion around $2 M_{\odot}$ and $1.5 M_{\odot}$, respectively, but Taylor does not believe that the difference is significant.

Irwin Shapiro of MIT, who has worked on many tests of general relativity, said that while he was impressed with the results he would be somewhat concerned about the statistical significance of the curvature, particularly in light of the gap in the data after 1975. Taylor agreed that the 1975 point appeared isolated, but he said that the remaining data show the same curvature, although with less statistical significance. He also felt confident about the reliability of the 1975 data, although they depend on less precise observations, because they do represent



Residual orbital period of PSR 1913 + 16 with respect to the initial observation. The uniform decrease in phase is due to an initial overestimate of the period. The second derivative of the theoretical curve represents the predicted effect of gravitational radiation from the system.

several months of observation.

Exactly what general relativity predicts for the orbital-period decrease is not completely clear. Taylor's group used a result from the standard, but approximate, calculation given (as an exercise) in the text by Landau and Lifshitz. The approximations, such as assuming the masses are moving slowly (compared to c) and are points, ought not to affect the validity of the result. Douglas Eardley, a theorist at Yale, believes that the exact calculation has not yet been done, and some recent work using approximation schemes gives different results. It is clearly a challenge to the theorists to clarify the situation, Taylor said, so that when further data give more precise results, they will serve to test the theory.

The data from PSR 1913 + 16 will have

an impact on other theories of gravitation as well. In fact, most other theories, but not general relativity, predict dipole radiation. Eardley and Clifford Will at Stanford have shown that, in general, the dipole radiation is larger than the quadrupole radiation predicted by general relativity. Because of symmetry, the dipole term vanishes when the orbiting objects are identical. However, the inferred near-equality of the masses is based on general relativity, Taylor told us; if other theories of gravitation are used in analyzing the data, the inferred masses may not be equal, so that dipole radiation would be expected. The pulsar observations may thus provide a crucial test for these theories. New data to refine the current results from PSR 1913 + 16 are eagerly awaited.

—TVF

Scanning acoustic microscopy

The resolving power of the scanning acoustic microscope now rivals that of the optical microscope. Since Calvin Quate and Ross Lemons reported building the first scanning acoustic microscope in 1974, Quate's group at Stanford has been able to improve the resolution of this instrument every year by about a factor of two; they now report they have achieved resolutions of about half a micron.¹ Quate recently described his progress in an invited paper at the March meeting of The American Physical Society in Chicago. Quate's group has also recently reported the results of the first experiment with a photoacoustic microscope,² a new instrument that generates sound waves by heating a sample with a pulsed laser.

Ultrasonic imaging has in recent years become a common tool of medical diagnosis. Such devices generate sound waves in the region of a few megahertz, corresponding to wavelengths of the order of a millimeter in water. By contrast, acoustic microscopy in Quate's lab is done at frequencies up to 3 GHz, producing wavelengths down to 0.5 microns in water at a temperature of 60°C. The resolution of such devices is determined by the velocity of sound in water (1.5 km/sec), because water is the medium generally used to couple the sample to the detector (and the source). Wavelength is proportional to propagation velocity. Joseph Heiserman of Quate's lab has developed an acoustic microscope designed to operate at temperatures as low as 2 K. With the reduced speed of sound in cryogenic liquids, the Stanford group looks forward to resolutions three times as good as those of optical microscopes by the end of this year.

Beyond the question of resolution, light and sound probe materials differently, yielding different kinds of information about the object under scrutiny. Sound waves can penetrate obscuring layers

opaque to light. While light microscopy senses variations in the (complex) refractive index, acoustic microscopes are sensitive to small changes in mechanical parameters such as elasticity. In cases of interest such acoustic parameters often exhibit significantly greater microscopic variation than do the optical parameters. The new photoacoustic microscope, which is something of a hybrid between these two classes of microscopy, is a sensitive probe of the variation of light-absorption characteristics in a structure.

The central component of Quate's acoustic microscope is a small sapphire crystal that can serve as both source and detector of the sound signal. One surface of the sapphire is flat, making contact with a piezoelectric transducer, while a hemispherical concavity in the opposite surface serves as an acoustic lens. In the reflection mode of operation, one such sapphire crystal serves as both source and detector; a transmission microscope will have two such sapphire devices—the source on one side of the sample and the detector on the other.

The piezoelectric transducer is a thin coating of zinc oxide that converts electrical rf signals to sound waves and vice versa, up to 3 GHz. The concave spherical lens has a radius of the order of a hundred microns (smaller at higher frequencies). It is covered by a very thin layer of glass that serves as an impedance match between the sapphire and the water that links the acoustic source (or detector) to the sample being observed. Water transmits sound much more efficiently than does air, but the attenuation rate increases as the square of the frequency. To achieve microscopy at 3 GHz, Quate and coworkers had to use a sapphire lens of focal length only 45 microns, and even over such a tiny interval they had to heat the water to 60°C to reduce attenuation.

Scanning acoustic microscope. The system operates as a scanning microscope, with the sample moving under the source in a raster pattern. The detected signal is displayed on a cathode-ray screen, with a frame consisting of several hundred lines. The scan rate produces several frames per second. The scanning acoustic microscope has been used to date primarily for non-invasive examination of biological systems and microelectronic circuits. Quate told us that the reflection mode of acoustic microscopy has proven more useful than the transmission mode. In the reflection mode, the acoustic signal is emitted in 20-nanosecond pulses, so that the Stanford group can isolate the reflected signal from the emitted signal at the source/detector by a time-gating circuit. For the study of highly polished non-biological systems, the reflection mode has presented no particular difficulties. But the Stanford group has only recently learned how to do reflection microscopy with biological systems mounted on ordinary slides.

With the rapid evolution of microelectronic technology, it has become important to investigate flaws in microcircuit elements manufactured by new techniques. These circuits contain structures of micron dimensions etched from semiconductor or metallic layers that are often only a few thousand angstroms thick. Quate believes that acoustic microscopy is well suited to look for flaws in such microstructures. The semiconductor patterns are frequently covered by metallic gates and other electrodes, which visible light cannot penetrate. Defects in construction and bonding can often be easily detected by the consequent spatial variations of the acoustic parameters of the structure. The non-destructive character of acoustic microscopy allows one to examine microcircuits under actual operating conditions.

In the years since Quate and Lemons built the first scanning acoustic microscope, several laboratories in this country and Europe have built similar instruments, but none of these have gone to the 3 GHz frequency where the Stanford group has achieved a resolution of 0.5 microns. Such high resolution is not essential for microcircuit examination. Rolf Weglein and Robert G. Wilson at Hughes Research Labs have examined integrated circuits in the reflection mode with a 375-MHz scanning acoustic microscope whose resolution was measured to be 1.7 microns.³ They were able to examine successive subsurface layers for voids, cracks and other defects by varying the object distance from the acoustic lens. The groups at Stanford and Hughes had shown that by moving the sample normal to the focal plane one can also identify and monitor the thickness of layers deposited on various materials such as sapphire, garnet and quartz by characteristic acoustic signals.

At still lower frequencies, Chen Tsai