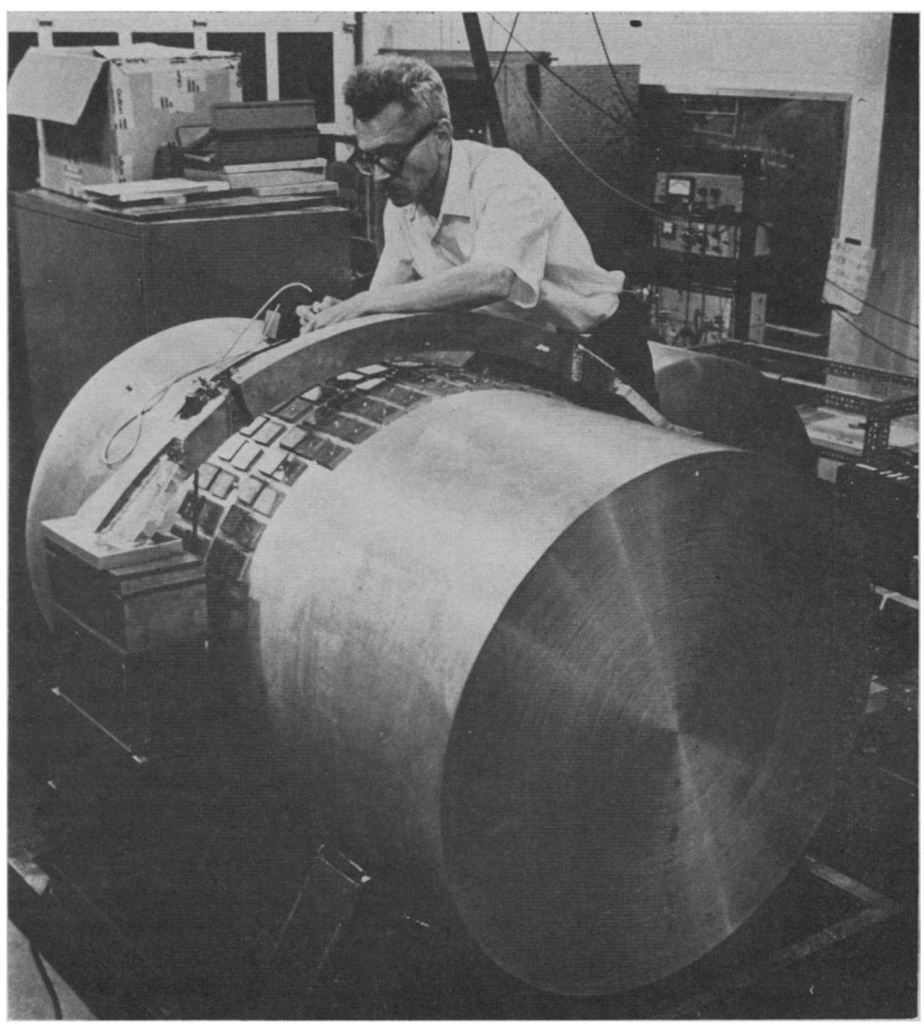
Gravitational Waves: The Evidence Mounts

When Einstein proposed the general relativity theory in 1916, he realized that his theory predicted the existence of gravitational waves. Similar to the generation of electromagnetic waves by moving charges, gravitational waves are generated by accelerating masses, such as binary stars, and propagate with the speed of light. Other masses, when crossed by the waves, should in turn undergo accelerations. But as any first-year physics student knows, the gravitational interaction is very small relative to the other forces. Since it is about 10^{40} times smaller than electromagnetic forces, detection of gravitational waves is extremely difficult. No attempts were made until 1958 when Joseph Weber began to design his laboratory experiments at the University of Maryland. Since then, Weber and his colleagues have dominated the experimental work in this field. Using suspended aluminum cylinders as detectors, they reported in 1967 their first indication of positive results for extraterrestrial gravitational waves. Improving his technique, Weber published results in June 1969 which are impressive. Nonetheless, many experts are skeptical. Most do not doubt the existence of gravitational radiation, but in view of the difficulty of the experiments, they would like to see more convincing evidence. Weber's latest results—published in February 1970—should, however, convert some of the skeptics.

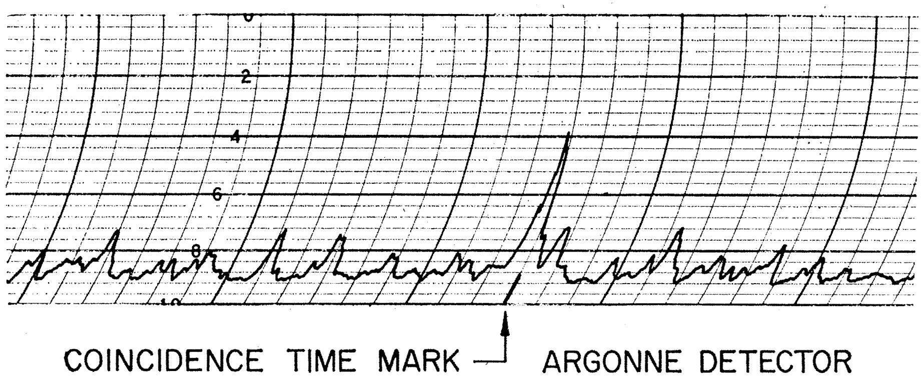
The properties of gravitational waves were originally deduced from weak field solutions or from linear approximations to the general relativity field equations. These equations are similar to the electromagnetic wave equations with the stress energy tensor playing the role of the source of gravitational fields and waves. In 1939, Pauli and Fierz derived a similar set of equations while investigating relativistic wave equations for particles of spin greater than one-half. Their equations for particles with spin two and zero rest-mass resembled Einstein's linear equations for matter-free space. It followed that the particles of the gravitational field—gravitons—have spin two and zero rest-mass. However, investigations of these quantum properties will have to wait for substantial improvement in the techniques of gravitational wave detection.

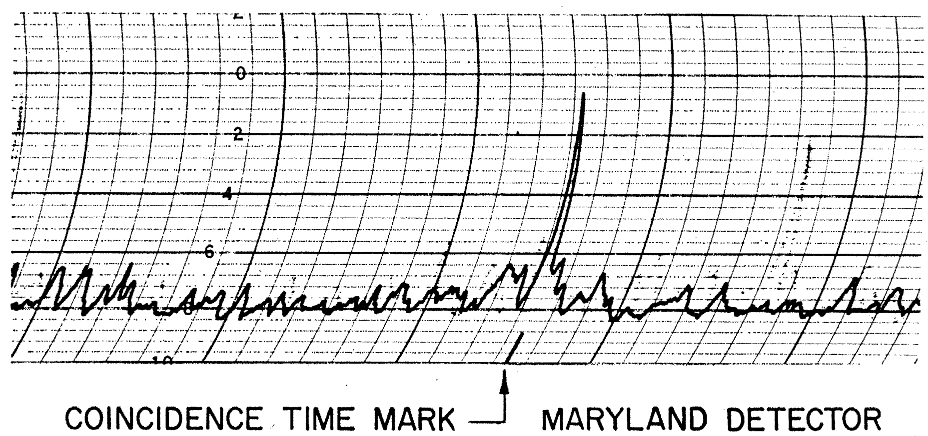
As most of the theoretical results were obtained from linear approximations to the nonlinear general relativity theory, they are being checked by more refined calculations. Although these investigations involve great mathematical complexity, much work has been done over the past 10 years. On the whole, there have been no worrisome conflicts with the linear approximations.

In order to observe the possible presence of gravitational waves, Weber decided to use a large aluminum cylinder suspended by a wire in a vacuum system. Quadrupole radiation—gravitational radiation possesses no dipole character—of sufficient intensity would excite the cylinder's normal modes of oscillation beyond the thermal noise level. In principle, the Brownian motion of the cylinder's normal modes should limit the accuracy of the experiment. Weber calculated that when the thermal energy is distributed over the aluminum cylinder, which weighs about 1400 kg, the random fluctuations of the end face amount to roughly 10^{-14} cm. This is a displacement of only 0.1 nuclear diameter. Weber pointed out that this motion is 10^{-10} of the wavelength of light, which precluded optical detection methods. As a result Weber, D. Zipoy, and R. L. Forward bonded quartz piezoelectric crystals to the cylinder's surface and observed the electric signal produced by the crystals when the



Coincidence events recorded by detectors located at Argonne National Laboratory and at the University of Maryland. At an American Physical Society meeting on 28 January, Dr. Weber reported that over 200 such coincidences have been observed. [From *Physical Review Letters*, with permission]





Joseph Weber shown with one of six detectors that he has built. Piezoelectric crystals bonded to the 4-ton aluminum cylinder around its center can detect strain produced in the cylinder by gravitational waves.

cylinder oscillated in its normal modes. A new technology employing titanate transducers bonded to the aluminum cylinder was developed in 1966 (*1*).

At present Weber has developed at least six such detectors which respond to gravitational radiation of frequency between 1 to 2 khz. This corresponds to wavelengths of about 10^7 cm. From theoretical arguments, it is predicted that, if the universe is filled with gravitational radiation due to the "big bang," most of it would oscillate at extremely low frequencies—possibly as low as 1 cycle per million years. Weber hopes that a high-frequency tail exists and is detectable, although it will not be as intense as the low-frequency radiation. Recent theoretical work indicates that these tails probably do exist (*2*). Since Weber observed no evident periodicity in his detector pulses, the high-frequency gravitational waves were most likely generated by random processes, such as collapsing supernovae. Binary encounters between stars in a nonrelativistic star cluster were recently discounted as possible sources of the pulsed gravitational radiation observed by Weber. Greenstein of Yeshiva University, who did the calculation, noted that the relativistic case is not explicitly ruled out (*3*). However, only massive relativistic clusters at large distances can emit radiation for an appreciable amount of time. The gravitational radiation of pulsars is discussed below. At present, the source of the gravitational radiation is still a mystery.

The problems of detecting gravitational waves are immense. Because of their small probability of interacting with the detector, all competing effects must be minimized. The one obvious source of background noise is acoustical vibrations generated "for example, by passing trucks or students marching around the campus" (*4*). To isolate the detector from this noise, a mount of acoustical filters was designed by Zipoy. It functioned so well, it was necessary to bang the vacuum system with a hammer in order to excite the normal modes of oscillation. Other obvious background effects could come from the earth's tremors and from electromagnetic radiation. Seismographs near the aluminum cylinders monitored the earth's motion. To test correlations of local electromagnetic excitations with gravitational radiation signals, Weber used a magnetic loop antenna tuned to a narrow band centered at 1662 hz. The antenna is at least six orders of magnitude more sensitive to electromagnetic signals than the measured electromagnetic response of the gravitational radiation detectors. No significant correlations of either seismic or electromagnetic effects with gravitational radiation signals have as yet been observed.

For his experiments reported in June 1969 Weber used four detectors. They were cylinders of 153 cm in length, which were tuned to a narrow band of frequencies centered near 1660 hz. Two of the cylinders had a diameter of 66 cm, the third had 96 cm and the fourth, 61 cm. As signals from one detector could be due to a variety of causes, including thermal fluctuations, Weber looked for coincident signals in two or more detectors. To avoid false signals due to earth movement, one of the 66-cm cylinders was located at Argonne National Laboratory about 1000 km from the others which were located at the University of Maryland. The signals were transmitted to Maryland via a telephone line. In a period of 81 days, the detectors recorded more than 17 significant two-detector coincidences, five three-detector coincidences, and three four-detector coincidences which could not be attributed to seismic or electromagnetic effects. From calculations of the probabilities for accidental events, Weber concluded (*5*) that "*all* of the coincidences can not be random." As the earth rotated on its axis, Weber was able to observe gravitational radiation in all quadrants of the sky. He found no preferred direction for the events. However, the latest results were suggestive of a source of gravitational radiation at the center of our galaxy.

In his latest paper, Weber reported over 100 detector coincidences covering the period 1 January through 30 November 1969. To counter previous criticism of his statistical analysis, Weber primarily concentrated on statistics and supported his analysis with new experimental evidence. Using delayed coincidences between the detectors, he showed that the observed number of accidental coincidences agreed with his statistical calculations. The accidental coincidence rate was measured by delaying one of the detector signals for 2 seconds before feeding the pulse into the coincidence circuit. As the resolving time of the coincidence circuit was less than 1 second, only accidental coincidences appear in the delay detector. Not only was the number of delayed coincidences significantly smaller than the number of prompt coincidences, but it was the same as the calculated number of accidental coincidences (*6*). Weber's claims that gravitational radiation is being observed appear to have won the numbers game.

Although Weber felt that he could adequately discount thermal fluctuations, and electromagnetic and seismic effects, recent work at Stanford University revealed another possible source of background signals. B. L. Beron and R. Hofstadter observed mechanical, or sound, vibrations in piezoelectric disks struck by 1-Gev electrons (*7*). They pursued this work with hopes of developing new types of high-energy particle detectors. From their electron results, they reasoned that all energetic particles should produce similar vibrations. In particular, cosmic rays impinging on large aluminum cylinders could cause normal mode vibrations. If this is the case, Weber's signals could be explained by the simultaneous occurrence of cosmic ray showers at each detector location. It is quite easy for Weber to test this hypothesis in future experiments. Cosmic ray detectors placed over his cylinders would indicate whether his gravitational waves are really caused by cosmic rays. At present he is investigating cosmic ray effects, but he does not think they could account for the observed coincidence rate.

The discovery of pulsars alerted Weber to the possibility of gravitational radiation at pulsar frequencies. He suggested that his apparatus could be modified to search for gravitational waves from pulsars (*8*). He also suggested the earth as a possible detector because it would absorb more gravitational waves owing to its large mass. However, seismic ground displacements might obscure any effects from pulsars. Freeman Dyson also investigated the seismic response of the earth to gravitational waves at pulsar frequencies (*9*). He concluded that the strength of the seismic signals expected from plausible models of pulsars were 10^5 smaller than the naturally occurring seismic background. Weber quoted a figure of eight orders of magnitude. However, both men emphasized that in view of the uncertainties in their calculations, attempts to identify the waves, with the earth as a detector, should not be discouraged.

Two geologists from M.I.T. took up the challenge at Dyson's suggestion. Ralph A. Wiggins and Frank Press observed data from the 525-element, large aperture seismic array (LASA) in Montana at the fundamental frequencies and at the double- and half-frequencies of four pulsars. From about 20 hours' worth of data, they saw no evidence for the expected gravitational waves. Their upper limit for the ground motion due to pulsars was about 0.01 millimicron—approximately 10^{-3} of an optical wavelength (*10*).

The moon is another natural detector, and Weber has plans to implant a gravimeter on its surface within the next few years. Another suggestion of Weber's is that the relative distance between the moon and the earth could be periodically changed by gravitational radiation from pulsars. He calculated oscillation amplitudes of about 4×10^{-12} cm. These hypothetical oscillations might be detected with the use of the laser corner reflectors placed on the moon by the Apollo astronauts. As yet, gravitational waves have not made an observable impression on either the earth or the moon.

One interesting consequence of gravitational radiation, based on Weber's results, has recently been explored by D. W. Sciama, G. B. Field, and M. J. Rees at Cambridge University (*11*). They indicated that the existence of galactic gravitational radiation would mean that our galaxy is losing mass energy, with concomitant galactic expansion. Using a simple model of galactic expansion, they calculated the amount of mass energy loss from astronomical data on stellar motions near the sun. The data, obtained from Doppler-shift measurements, supplied direct evidence that our galaxy is expanding. For their calculation, Sciama and his colleagues accepted this evidence, but the interpretation of the data is still unsettled. They also assumed that mass was lost from the galactic center—as indicated by Weber's data—over a dynamical time scale of about 10^8 years. Their assumptions placed an upper limit on the amount of mass loss of 200 solar masses per year. This is consistent with the flux of gravitational radiation claimed by Weber, if the radiation is assumed to be wide band radiation. As Weber only took measurements in a narrow band of frequencies, this assumption has not been checked.

The Cambridge results agree with another observation. Namely, the stars and gases of all types and ages in the vicinity of the sun move outward at the same average velocity. M. Schmidt had stressed that this phenomenon could be understandable only if the gravitational potential varies with a characteristic time of about 1 billion years. Accordingly, Sciama, Field, and Rees suggested that the galaxy is indeed expanding as a result of mass loss and that this had been occurring for at least 10^8 years. From the estimated rate of mass loss, the galaxy would have lost a mass about equivalent to its present mass in 10^9 years.

In another paper, Sciama reported the expected features of a galaxy which lost half of its mass in 1 billion years (*12*). His primary expectation was that no stars with orbital periods greater than about 1 billion years would be bound to the galaxy. He then examined a large amount of astronomical data to find supportive evidence for his hypothesis. Many of the experiments conformed to his model, and the remaining ones did not contradict it. He concluded that the experimental results "do not provide clear cut evidence against the hypothesis that the galaxy is losing mass on a time scale of a billion years. Bizarre as this hypothesis may seem, its rejection or confirmation will have to await further experiments on the flux of gravitational radiation in the vicinity of the Earth." Considering the interest in this field, experimental groups throughout the world are now developing new equipment for detecting gravitational radiation.

Gravitational waves are definite non-Newtonian phenomena. If their existence can be clearly demonstrated, general relativity theory would receive additional support. Both Einstein's theory and that of Brans and Dicke allow for gravitational waves, but they would be of a different nature. Weber mentioned that certain cylinder modes can be excited by the scalar component of a gravitational field. As Einstein's theory does not contain a scalar component, the scalar modes of the cylinder would provide a possible test for the Brans-Dicke-Jordan scalar-tensor theory.

—GERALD L. WICK

References

1. J. Weber, *Phys. Today* **21**, No. 8, 34 (1968).
2. W. B. Bonner, *Status of General Relativity* (Hodgson, London, 1969). p. 14.
3. G. Greenstein, *Astrophys. J.* **158**, L145 (1969).
4. J. Weber, in *Gravitation and Relativity*, H.-Y. Chiu and W. E. Hoffman, Eds. (Benjamin, New York, 1964), chap. 5.
5. ———, *Phys. Rev. Lett.* **22**, 1320 (1969).
6. ———, *ibid.* **24**, 276 (1970).
7. B. L. Beron and R. Hofstadter, *ibid.* **23**, 184 (1969).
8. J. Weber, *ibid.* **21**, 395 (1968).
9. F. Dyson, *Astrophys. J.* **156**, 529 (1969).
10. R. A. Wiggins and F. Press, *J. Geophys. Res.* **74**, 5351 (1969).
11. D. W. Sciama, G. B. Field, M. J. Rees, *Phys. Rev. Lett.* **23**, 1514 (1969).
12. D. W. Sciama, *Nature* **224**, 1263 (1969).