Gravitational waves—a progress report

Although many experiments to detect gravity waves are underway, and others are planned, so far none of them has reproduced Joseph Weber's results, first reported in 1967.

Jonathan L. Logan

For over ten years Joseph Weber has conducted a search for the gravitational radiation predicted by general relativity. His recent results indicate an apparent powerful source of radiation at the galactic center. More than a dozen groups have now joined the effort, and several have reported preliminary results; so far no one has reproduced Weber's findings. The pace of research is accelerating, and this appears to be a good time to discuss the current experiments and those planned for the next few years.

According to Einstein's (geometrical) field theory of gravitation, a disturbance in the local geometry of space-time, propagating at the speed of light and transporting energy, would be produced whenever matter is violently accelerated in a nonsymmetrical way. These gravitational waves would, for example, produce fluctuations in the distance between two nearby test bodies at the frequency of the wave and so could, in principle, be detected. The detection of this radiation would represent a qualitative advance in experimental science: Not only could one test the radiation theory, but one would also hope to get information about the astronomical sources and test also (indirectly) the nonlinear aspects of the theory in the situations where intense gravitational radiation would be produced.

The gravitational coupling of matter is ridiculously weak. If only gravity bound the hydrogen atom, the radius of the first Bohr orbit would be 10^{13} light years (a thousand times the Hubble radius of the universe; Richard Feynman has other, even better, examples[1]). So the experiments are very hard to do—especially tests of the non-Newtonian parts of the theory. Until about fifteen years ago, nobody even tried seriously to observe gravitational radiation.

Since 1967 Joseph Weber, at the University of Maryland, has reported signals that he believes are due to gravitational radiation. A number of experimenters have recently tried to reproduce these results in similar, but not identical, experiments: So far they have not found anything.

The experiments of Joseph Weber

In an essay published in 1959[2] Weber examined the theory of the generation and detection of gravitational waves and determined that an attempt to construct laboratory apparatus or an experimental study of the predictions of general relativity would be worthwhile. This was at a time when it was not yet completely clear that the theory allowed for the existence of observable radiation, and at a time when essentially none of the requisite technology was in existence, even in the engineering literature.

Weber developed plans for a laboratory-sized resonant mass-quadrupole detector based on the observation of minute strains in a massive isolated aluminum cylinder.[3,4] (The disc antenna shown in figure 1 operates on precisely the same principle, but with a different geometry.) Radiation incident normal to the cylinder axis would excite the longitudinal compressional mode of the cylinder (corresponding to the fluctuations in distance between two test particles), so producing strains that could be measured with ultrasensitive piezoelectric strain transducers. He implemented the plans in a design so elegant and so definitive that almost every laboratory experiment constructed, or under construction, since then has followed his original basic design.

The operation of a prototype experiment was reported at a relativity conference in Warsaw in July 1962. Weber did not interpret these first fragmentary results ("... these bursts—the recorder suddenly moving off scale in the stillness of the night ..."[5]) as ev-

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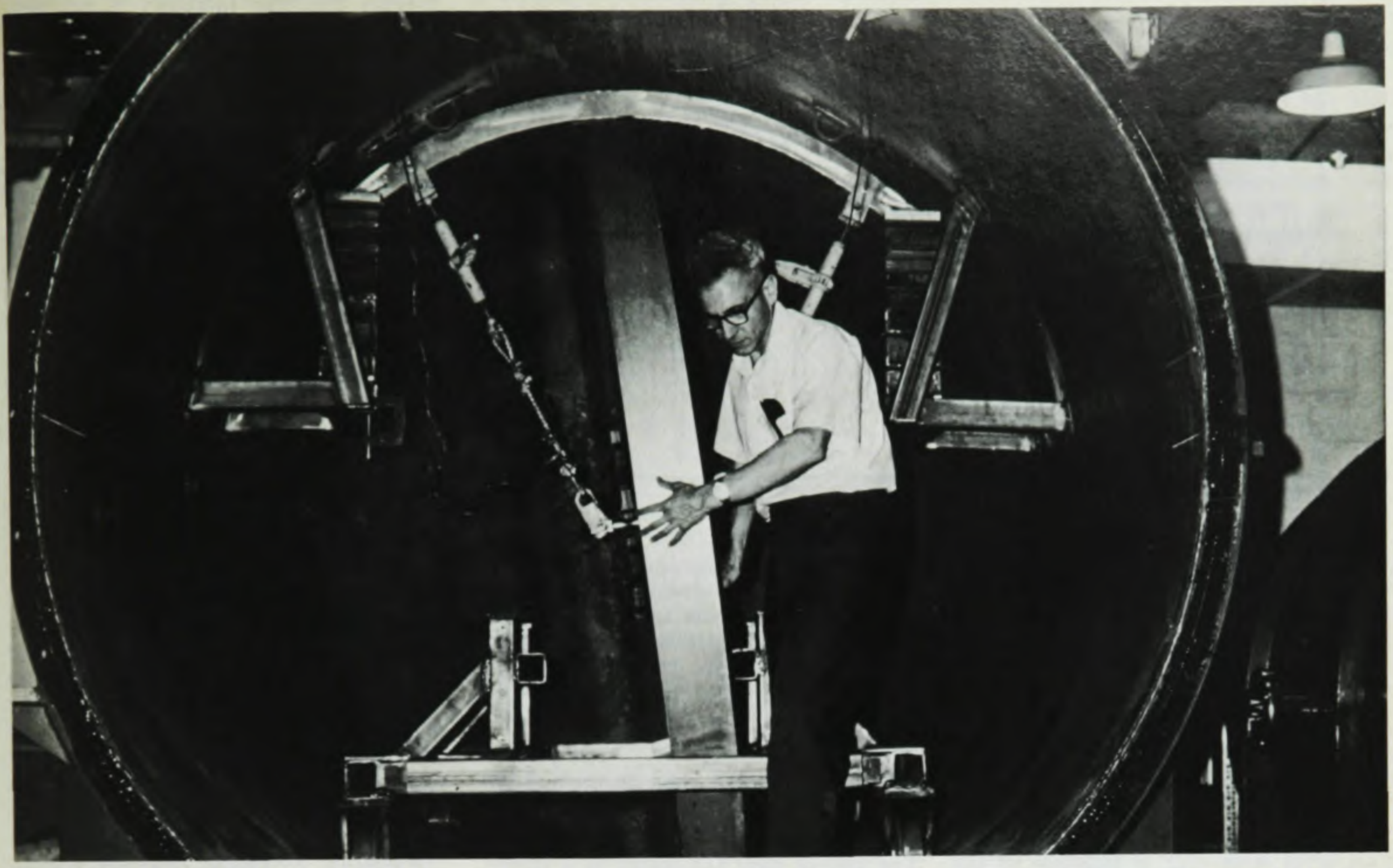


Joseph Weber with the large aluminum disc antenna in his laboratory at the University of Maryland. The disc, with a mass approximately equal to that of Weber's cylinder antennas, is instrumented to record separately strains in two modes of different symmetry, which could be produced by scalar radiation at 1660 Hz and tensor radiation at 1030 Hz. Figure 1

idence of gravitational radiation, and he observed for two full years before he reported the first preliminary results of ten "events" in an experiment with a 1½-ton cylinder at 1657 Hz in 1967:

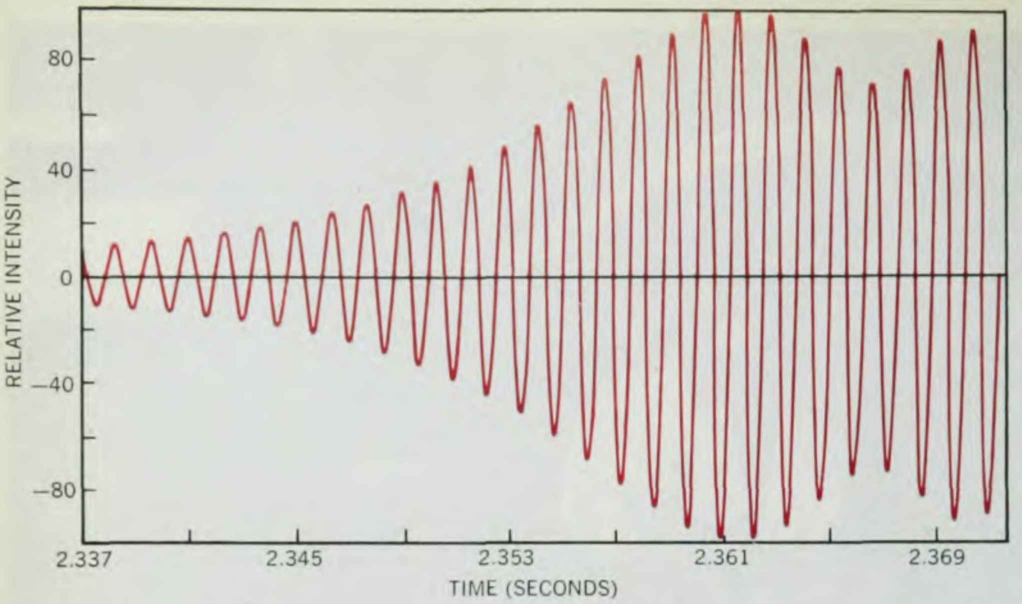
> "The gravitational-wave detectors record isolated events which are not detected by seismometers, gravimeters, tilt meters, or devices responsive to only electromagnetic fields, of types currently in use .... The possibility that some gravitational signals may have been observed cannot completely be ruled out."[6]

At the same time Weber reported a study of the noise output of a gravimeter of special design that gave an upper limit for the flux of gravitational radiation incident on the earth in the one-cycle-per-hour regime.[6,7] In the preceding year he had reported[8] observation of the thermal fluctuations of the antenna cylinder (given by the classical equipartition theorem for a harmonic oscillator at room temperature and with $m = 1\frac{1}{2}$ tons!), which required the measurement of strains as small as a few parts in 10^{16}. This corresponds to the thermal root-mean-square displacement of the cylinder faces of approximately 2×10^{-14} cm (a tenth of the classical electron radius!) over a 1½-meter bar—an order of precision without precedent in such measurements. Shortly thereafter Joel Sinsky and Weber reported[9] a measurement of the 1660-Hz dynamical gravitational field produced by a smaller aluminum cylinder acoustically stressed almost to the breaking point, a high-frequency dynamical Cavendish experiment. This is equivalent to a "very-near-zone" experiment in electrodynamics.

In 1969 Weber reported[10,11] 17 "events," simultaneous excitations (within the approximately 0.4-sec resolving time of the apparatus) of a detector at his laboratory at the University of Maryland in College Park and of an identical detector in his laboratory at the Argonne National Laboratory near Chicago, 1000 km distant. Both cylinders are suspended horizontally and aligned east–west; they are not quite parallel because of the finite radius of the earth. Some of the events also involved excitation of three and four detectors, and all of them involved energies about equal to the average noise level. The thermal fluctuations of the two antennas are of course statistically independent, so that a correlation in the outputs would be evidence of excitation by a common signal. Weber offered a statistical argument that not all of the coincidences could be due to chance, and concluded that a common signal was exciting the distant detectors. Concurrent seismic and high-frequency electromagnetic monitor experiments indicated no significant correlation of the events with such disturbances, and Weber reported that "These data are consistent with the conclusion that the detectors are being excited by gravitational radiation."[10]

Although there was a very serious error in the statistical argument, a correct analysis still yielded an excess of coincidences over the chance rate. Since most of the plausible sources of a simultaneous disturbance over a baseline of 1000 km were investigated and ruled out, it was strongly believed that gravitational radiation had been observed. Weber has searched for possible correlations with solar flares, electric storms, surges in the interstate electric power grid, network television broadcasting, and seismic events; D. H. Ezrow, N. S. Wall, Weber and G. B. Yodh[12] measured the cosmic-ray flux at one of the sites with a large scintillation counter and found no significant correlation with the events.

Nonetheless R. A. Adamyants, A. D. Alekseev and N. I. Kososnitsyn[13] have recently suggested that a significant correlation might exist between the events of references 9 and 10 and various terrestrial, solar, and cosmic-ray activities. Tony Tyson, C. G. Maclennan and L. J. Lanzerotti[14] have examined data supplied to them by Weber



Response of an idealized resonant detector to the burst of radiation expected from a star or binary system collapsing from $R = 25\, R_s$ to $R = 3\, R_s$ in 2.4 sec, where R_s is the appropriate Schwarzschild radius of the system. The response is quite different from that due to the step-function excitation assumed by several authors. For this computer calculation, Weber and Clemens have chosen parameters corresponding to the configuration of the antennas in Weber's experiments. (From reference 27.) Figure 2

representing 262 events in a four-month period in 1969 and discovered a correlation at the 2.7 standard-deviation level with D_{st}, a measure of the magnetospheric ring-current intensity, and have speculated on possible coupling mechanisms. Because a correlation as such cannot be proof of a causal relation, the implication of any correlation at this level is perhaps uncertain.

Sidereal anisotropy

In July 1970, Weber published[15] histograms of "detector intensity" (computed in an attempt to assign appropriate weights to events of different magnitude; the results are substantially unchanged if the number of coincidences is considered instead) plotted in two ways. One plot was against solar time, and the other was against sidereal time (reckoned according to the rotation of the earth with respect to the stars, different from solar time by one day per year). Both plots covered the period 12 May–14 Dec. 1969.

The plot in solar time yielded a typical random sort of distribution; the sidereal plot showed impressive maxima centered around approximately 18^h and 6^h R.A. (Right Ascension). At sidereal times $17^h\,43^m$ and $5^h\,43^m$ the antennas are oriented for maximum sensitivity to radiation from the center of the galaxy; Weber concluded that "The location of the peaks suggests that the source is the 10^{10} solar masses at the galactic center."[15] The directionality of the antennas is such that additional data (or assumptions) are required to determine unambiguously the location of the source; D. H. Douglass and Tyson[16] have shown that for randomly polarized emission, several loci (including the galactic center) are consistent with the reported directional dependence. See also reference 17. The twelve-hour symmetry is a consequence of the near-unity transmission coefficient of the earth for gravitational radiation and of antenna symmetry.

Weber had earlier reported[18] data from the overlapping period 18 February–18 July 1969, which showed a kind of anomalous sidereal effect—a peak around $17^h\,43^m$ R.A. but a *minimum* around $5^h\,43^m$.

Valdimir Braginskii, Yakov Zel'dovich and Valentin Rudenko performed an analysis of a summary of Weber's data from still another, overlapping, period in 1969 and concluded that ". . . in (their) opinion, the hypothetical radiation from the galactic center is not confirmed."[19]

Results from experiments since 1969 continue to show a sidereal time dependence;[20,21] data from the period 20 May–20 November 1970 show a peak in the direction of the galactic center. Weber states that "For the two cylinders the front-back 12h symmetry has been demonstrated in three independent six-month experiments with peaks in the direction of the galactic center."[21] However, all of the results reported since 1969 have been plotted in six-bin histograms folded to three bins (to obtain better statistics), so that the question is somewhat obscured.

Astrophysical sources

Since the results so far are insufficient to localize the source with certainty, and because the bandwidth of the receiver is only about 0.03 Hz (although evidence from other experiments implies that it would be safe to assume that the intensity is not very different over a bandwidth of about 1 kHz), it is necessary to make some definite assumptions about the source before we can estimate the total energy flux and the total energy emitted. Supposing an isotropic emitter at the galactic center (about 9.5 kiloparsecs away), Weber estimated that the observed event rate would correspond to the total conversion of 1000 solar masses per year into gravitational radiation.[15] Other estimates have ranged to 10 000 solar masses and higher.[22]

Such a source would be the most powerful in the history of astronomy by a factor of perhaps one million, producing almost exclusively gravitational radiation, apparently, since no significant correlated optical, infrared, or radio emissions have so far been reported. D. W. Sciama, G. B. Field and M. J. Rees[23,24] have reasoned that an energy loss greater than about 70 solar masses per year on a continuous basis would produce other observable effects in the galaxy, but these are not observed. (Of course the source could be closer than the galactic center, or shortlived, or it could be producing highly directed radiation: So far there are no satisfactory models of this kind.)

Freeman J. Dyson pointed out in 1962[25] that close white-dwarf (or neutron-star) binary systems would be powerful emitters of relatively high-frequency gravitational radiation, especially in the final stages of evolution (see also references 26–28) and he suggested that Weber look for them. (In reference 25 Dyson was concerned with the side-effects of a technology that provided the means to set stars into convenient orbits at will!) Fairly close systems, such as Nova WZ Sagittae, have been observed since then (see chapter 7 in reference 28 and citations therein). More recently[29,30] Dyson has pointed out that the coupling ϵ between gravitational waves and shear waves in a body is of the order

$$\epsilon = \frac{G\rho}{\omega^2}\left(\frac{s}{c}\right)^3$$

For the aluminum cylinders used so far in the terrestrial experiments both factors are about 10^{-15}, but for neutron-star cores the shear-wave velocity s is about $0.3c$, and the density is so great that both factors are of order 1, so that nonradial pulsations of a neutron star could generate radiation of tremendous intensity. (Conversely, a neutron star would be a superb gravity-wave detector, if only we could install a gravimeter on one!) Pulsars, the quasi-stellar objects, and systems involving collapsing, and collapsed objects (the so-called "black holes") are also very interesting potential sources of intense radiation. Wheeler[28] has given a very extensive discussion of possible sources and of the experiments; a somewhat more recent discussion is in ref. 22.

Weber and R. W. Clemens[27] have calculated the response of an idealized detector to the kind of radiation expected from collapsing stars and binary systems (see figure 2).

In 1971 Weber reported[21] some results of experiments with a new disc antenna (figure 1) operated in coincidence with one of the cylinder detectors. Because the radial mode of the disc would not be excited by quadrupole radiation incident along the axis, but would respond to scalar radiation, it is possible to search selectively for such radiation—which is predicted, for example, by the gravitational theory of Carl Brans and Robert Dicke[31]. Weber reported no evidence for such a scalar component. In the Brans–Dicke theory the gravitational field is made up of both scalar and tensor components (the proportion fixed by a parameter determined from experiment), and the proportion of the two types of radiation emitted would depend on the character of the source. Hence the absence of a large scalar component would not constitute a contradiction to the theory at this point.

Since the disc has modes of different symmetry, it is also useful for measuring the state of polarization of the radiation. This experiment is underway; two years of observation would be reouired for an accurate measure. The experiment provides another piece of information: The event rate is not less, for the 1030-Hz quadrupole mode,[30] than for the 1660-Hz cylinder, so it is possible to conclude that the intensity of radiation is not less than at 1660 Hz. Thus one obtains an estimate of the minimum bandwidth of the radiation.

Weber's most recent paper[32] reports a computerized analysis of some data: Magnetic tapes, on which are written the outputs of the Argonne and Maryland detectors, are searched for coincidences satisfying definite criteria, so making human intervention unnecessary. A time-delay experiment, performed by running the coincidence analysis with one channel delayed by various fixed amounts, shows a very large peak at zero delay.

Unfortunately a possible serious weakness remains in the experiment, namely that the data from Argonne are brought to Maryland (digitized but then reconverted to analog form[32]) over telephone lines in real time, to be analyzed and recorded in the same room in College Park. Any sufficiently strong disturbance that somehow penetrated the shielding here could evidently be responsible for a "coincidence." Weber plans to change over to independent local recording of the data as soon as the system can be perfected.

Weber is developing several variants of the experiment, including a cryogenic system and a high time-resolution experiment. He is analyzing data from the lunar seismic experiment described below, and he continues to improve the experiments. The disc and cylinder receivers are currently operating, with a coincidence rate presently of about three per day.

Other laboratory experiments

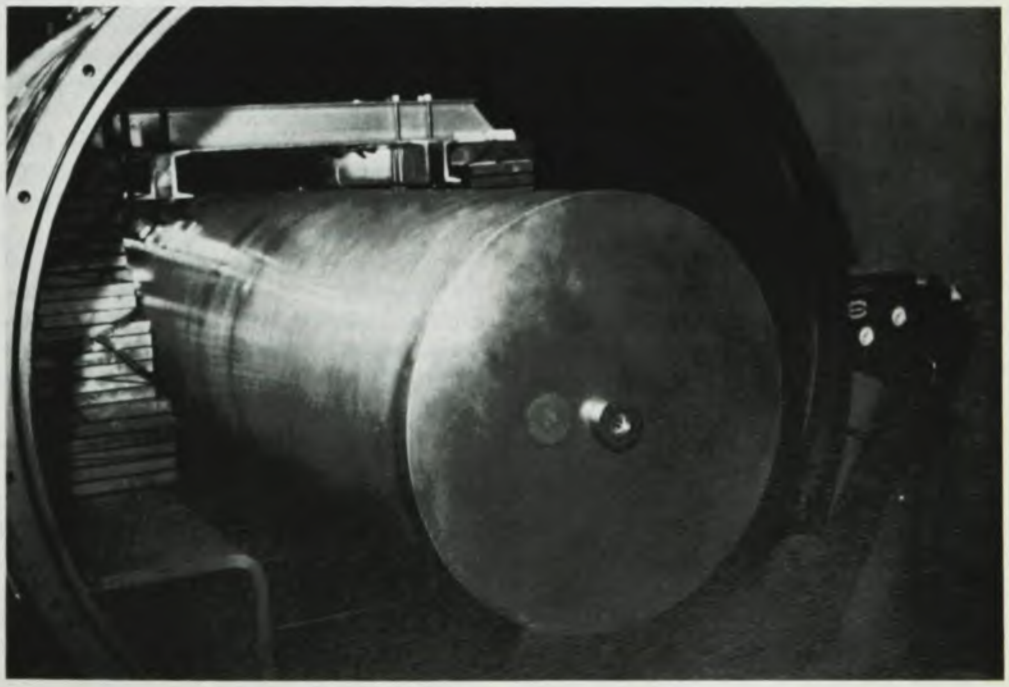
Ronald Drever, at the University of Glasgow, is operating a pair of detectors somewhat smaller (one-third the mass) than Weber's, after the "sandwich" design of Peter Aplin. Each detector consists of two aluminum cylinders joined end-to-end with a layer of piezoelectric transducer material, to achieve better electromechanical coupling than is possible with crystals glued to the girth of the cylinders.[33] The system is calibrated by introducing mechanical shocks through capacitor endplates with a short pulse of current and measuring the response. With an elaborate pulse-height analyzer system Drever studies the signal in great detail and with excellent time resolution and performs, continuously, a time-delay experiment between the two detectors. The signal is taken on magnetic tape, so making correlation and spectral studies possible. So far, in a year's running with one detector and six months with two, no correlation between the outputs (peak at zero delay) has been found and no definite "events" have been seen. However, 20 marginal individual events and one unusual event, a simultaneous excitation of the two detectors satisfying Drever's criteria, have been observed, but unfortunately none of the other groups were operating at that moment, so no comparison was possible. Drever has also looked for correlations on a broader time scale. In a small sample of data he found a two-standard-deviation peak at zero delay, at about 100 millisec resolution. Other runs showed no such correlation, and he does not regard it as a real effect.[30]

Drever estimates the sensitivity of his apparatus as somewhat less than Weber's, and because his signal-analysis program accepts "events" only if they satisfy requirements of simultaneity, phase and amplitude considerably more rigorous than those imposed by Weber, it is not yet possible to make a definitive comparison with Weber's results.

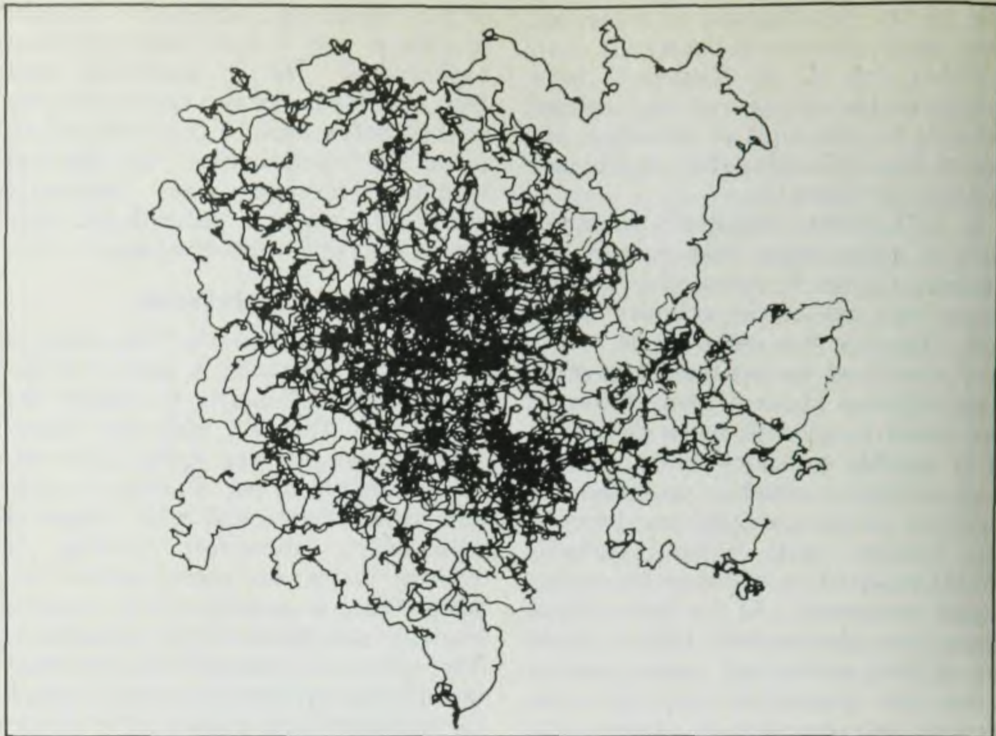
Note particularly here that all comparisons of sensitivity and calculations of intensity bounds may depend in a significant way on the type of signal assumed.

Drever's antennas are presently operating, and he plans to build two more, and possibly to operate in coincidence mode with one or more of the other groups in the future.

One year ago J. A. (Tony) Tyson[30,34] began operating a receiver at Bell Laboratories in Holmdel, New Jersey. His detector is a 12-foot, 8000-pound aluminum cylinder, with its main longitudinal mode at 710 Hz and a mechanical Q of about 6×10^5. (See figure 3.) The system is very much like Weber's, but with a considerably larger cross section and some refinements of



J. A. Tyson's antenna at Bell Laboratories in Holmdel, N. J. The main longitudinal mode of the 8000-pound, 12-foot cylinder occurs at 710 Hz. On the right is part of the air-flotation support system; within the vacuum chamber near the support blocks on the left is one of four sets of piezo-electric crystals, arranged symmetrically about the girth of the cylinder. Two types of accelerometers are visible on the endface. Figure 3 detail. Piezoelectric crystal transducers are glued in four sets, symmetrically placed about the girth of the cylinder, wired in series to cancel—or at least partially cancel—output due to the first bending mode of the cylinder, which should not be excited by quadrupole radiation; the output from accelerometers on an endface is also measured. The cylinder support floats on an air-suspension system for increased seismic-acoustic isolation, and it is heavily shielded against electromagnetic disturbances. The output from the crystals is amplified and (linearly) detected and taken on magnetic tape for analysis, and also compared to the output of a precision oscillator running at the main longitudinal-mode frequency (see figure 4). The data analysis consists of a search of the tape by computer for events corresponding to the excitations Tyson infers that Weber has seen—sharp excitations followed by a slow decay (ringing time of the antenna approximately 100 sec). The search is done by convolving the output continuously with the waveform expected for a "Weber event." Tyson also compares the differential energy spectrum of the output with the Rayleigh distribution expected for thermal noise. The system is calibrated by injecting mechanical pulses to the antenna through a capacitor endplate. Seismometers, a magnetometer, and a sensitive microphone tuned to the resonant frequency of the cylinder quadrupole mode are continuously monitored. (Most of the groups are using some such precautions, because all of the systems have some sensitivity to such excitations).



Random walk in phase space. This is an xy-recorder plot of the detected narrowband-amplified output of the strain gauges on the large cylinder at Holmdel compared in phase and amplitude (polar display) to the output of a precision oscillator set at the main quadrupole-mode frequency of the cylinder, 710 Hz. A sudden pulse signal would appear as a long straight section of trajectory. (Figure supplied by J. A. Tyson). Figure 4

In 1971[20] Tyson reported a coincidence experiment run for several months with two miniature prototype cylinders at Murray Hill, N. J., and Rochester, New York. These models had 1/400th the cross section of the present antenna, and were resonant at 4.2 kHz. Tyson's very preliminary data show a one-standard-deviation peak in the direction of the galactic center, which he has dismissed as a statistical accident.

The large antenna detector has been on the air with increased sensitivity since early December, 1972; Tyson recently summarized his findings for the author as follows:

> "No sudden excitations of magnitude larger than half the Brownian motion have been observed in the Holmdel gravitational wave antenna in 6 weeks of continuous observation. From my estimate of Weber's maximum possible sensitivity, this corresponds to the nonobservation of pulses of gravitational radiation at 710 Hz of a flux that would correspond to 1/200th of Weber's energy resolution in 1970. Further observation with two antennas in coincidence will permit an even lower flux limit to be set if no coincidences above the chance rate are observed."

This evidently constitutes a null result. Because the experiment has been running for only a relatively short while, because the detector is sensitive at 710 Hz rather than 1660 Hz (although, as we remarked before, there is reason to suppose the intensity should be comparable at this frequency), and in view of the calibration question discussed below, a coincidence experiment may be required for a definitive comparison with the results of Weber.

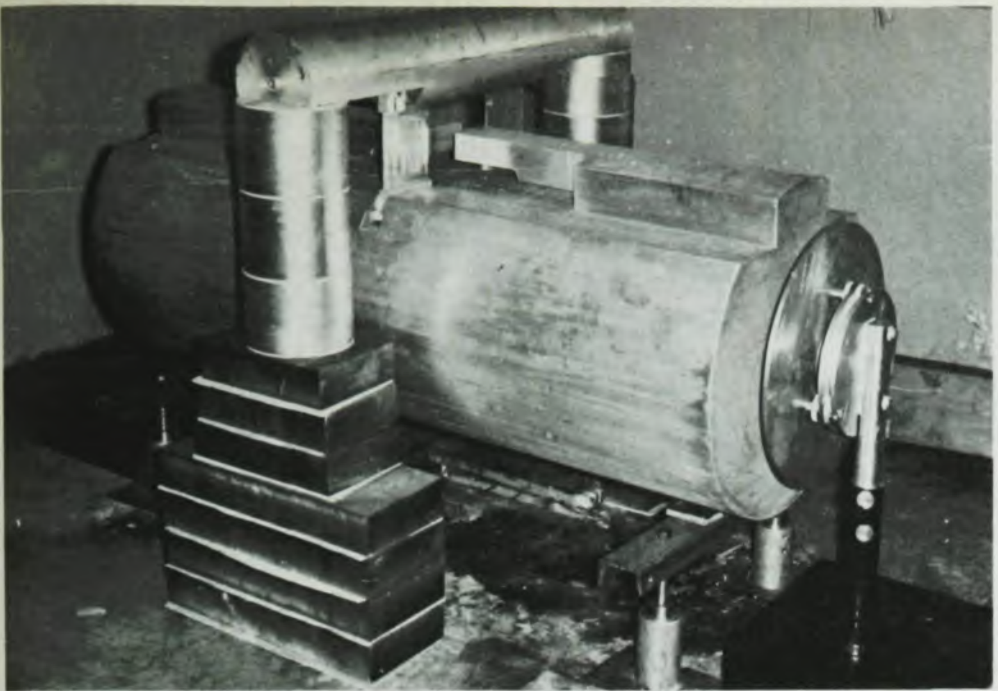
At present Tyson sets an upper limit of 3×10^4 ergs/cm^2 sec Hz for the flux intensity per cycle of bandwidth at 710 Hz for pulse-type events, and of 3×10^6 ergs/cm^2 for the total energy density per pulse. He plans to begin a coincidence experiment with an identical experiment performed by David Douglass at the University of Rochester by early spring.

Vladimir Braginskii, at the Moscow State University, has operated a two-detector experiment for a total of twenty days so far.[35] His detectors use cylinders very like those in the Weber experiments, but with a novel and very elegant detection scheme, and with local recording of the output. The ends of the cylinders are projected out to the top (see figure 5) and almost, but not quite, meet, so that the intervening space can serve as the cavity of a parallel-plate capacitor, which is wired as one arm of an rf bridge circuit. Hence one measures displacements rather than strains. Very small relative displacements of the "capacitor plates" produce an imbalance in the bridge, and the signal is detected, amplified, and recorded on an oscillograph. In the piezoelectric transducer systems, the detected signal energy is produced by the crystals and amplified, whereas in this scheme the energy is supplied by the external rf source. So the ultimate sensitivity is no longer limited in the same way by the small original signal, and the theoretical limit is very considerably better. The apparatus is calibrated by introducing mechanical excitations via the large capacitor endplate visible in figure 5.

In the observations so far, Braginskii's group reports several dozen nonthermal excitations per day and approximately 30 "suspicious places" where nearly simultaneous pulses were recorded at the two sites. Because the waveforms of the pulses were very different at the two receivers, and for other reasons, they do not regard them as genuine coincidences produced by a common source (and not as due to gravitational radiation).[35]

At this writing the experiment has been taken out of operation for improvements, but should be in operation again within a few months. Braginskii plans to operate an array of nine stations across the reaches of Soviet Siberia, and he hopes to improve the time resolution sufficiently to observe phase differences between the stations, to determine the velocity of propagatation with more noise, substantially different data processing or very different quality factors."

It is probably essential to perform a two-detector coincidence experiment with at least comparable sensitivity in order to make a definitive comparison with Weber's results.



Antenna of one of the gravitational radiation detectors in the laboratory of V. B. Braginskii at the Moscow State University, outside its vacuum chamber. The 1300-kg cylinder has a mechanical Q of 100 000 and a main quadrupole-mode frequency of 1640 Hz. Visible are the metal and rubber isolation-support blocks, a large capacitor endplate for injecting electromechanical pulses, and the extensions of the ends of the cylinder to the top to form the plates of the "output capacitor." (Photograph kindly supplied by R. H. Dicke, used with the permission of V. B. Braginskii.) Figure 5

tion of any signals observed. If several of the receivers are tuned to different frequencies, it could be possible in addition to resolve in time the swept-frequency radiation that is expected, for example, in the collapse of a binary system.

Richard Garwin and James L. Levine, at the IBM Research Center in Yorktown Heights, New York, have instrumented a detector based on a small aluminum cylinder 5 feet long and 7 inches in diameter operating at 1660 Hz but of one-tenth the mass of Weber's cylinders.[36] Strains are measured by examining the signal from piezoelectric material suspended between an isolated seismic mass and the end of the cylinder, and the system is calibrated by measuring its response to electrostatically induced mechanical shocks. The output is measured every 0.15 sec and stored; analysis of the data consists of processing the output signal to eliminate the correlations introduced by the ringing of the bar and to enhance any step excitations corresponding to the kind reported by Weber, and of searching for such signals. With an instrumentation noise-temperature of approximately 33 K, Garwin and Levine report that they are able to detect, with a background of less than one per day, pulses producing excitations in the main cylinder longitudinal mode of equivalent temperature 500 K (roughly 1.7 kT for room temperature). From the prompt/delayed correlation data recently published by Weber,[32] and the instrumentation parameters published some time ago, Garwin estimates that the events observed a few times per day by Weber must have produced excitations in Weber's apparatus of energy 8000 K, which would produce excitations in the Yorktown Heights apparatus of energy 800 K, and which they would expect to observe with 60 or 70% efficiency. So far, data for only a few days' running have been reduced, and they show no excitations of such strength. The probability distribution of the output is consistent with the Boltzmann distribution of pure thermal noise. The receiver is presently operating, and ways of improving sensitivity, and of possibly expanding the experiment, are being considered.

Results compared

Weber reports that he has calibrated the receivers and that noise-temperature measurements, performed at intervals, establish that the total noise temperature does not differ greatly from room temperature.

Weber recently provided a statement on the present status of the experiments:

"More than ten groups of physicists, worldwide, are now doing research of high quality ... It is most unusual that at this time, January 1973, no one has repeated the 1969 Maryland–Argonne coincidence experiments with similar or improved instrumentation and data processing. Other experimental groups have either employed smaller detectors, instrumentation with more noise, substantially different data processing or very different quality factors."

However, Braginskii's group,[35,37] Tyson and Miller,[30,34] and Garwin and Levine[36] have calculated the noise temperature and maximum sensitivity of Weber's receivers independently on the basis of the published experimental results[32] and instrumentation parameters,[38] and have concluded that the actual effective sensitivity is at least ten times less than reported. If this is right, then definite comparisons between the results of Weber and those of the experiments described are already possible. Again it must be borne in mind that estimates of sensitivity may possibly depend strongly on the character of the assumed excitation. Nonetheless, the theory of the detection of very small signals in noise is by now well developed, so that it should soon be possible to provide an answer.

Other experiments underway

Robert Forward and Gaylord Moss at Hughes Laboratories have developed a wideband (0.5–24 kHz) receiver based on a Michelson interferometer with heterodyne detection of coherent light.[39] One measures the difference in the optical path length, between two (or more) loosely suspended bodies some distance apart, that would be produced by gravitational radiation. (See figure 6.)

Forward and Moss have operated a detector with a folded optical path length of 2.1 m, giving a total effective antenna length of 8.5 m, for two months so far, but they have analyzed completely only a fraction of the data (about 15 hours). They find some "unusual" signals (about one every three hours), which were not registered on audio and seismic monitors. The source of these has not been found, but Forward and Moss do not interpret them as due to gravitational-radiation excitation. Measurements of 8×10^{-6} Å displacements (limited partly by photon noise!) have already been accomplished with the system; because such displacements are very much less than optical wavelengths, ordinary fringe-motion interferometry is inadequate. The receiver is very much less sensitive than existing high-Q (resonant) detectors, but it has the advantage of large bandwidth and considerable potential sensitivity, since the antenna length can be extended to kilometers or more.

Rainer Weiss at MIT is planning a similar detector; his is a laser interferometer with a single active leg.

Judah Levine, at the Joint institute for Laboratory Astrophysics, is operating a long-baseline laser interferometer to measure strains in the earth's crust, and is looking especially for response at pulsar frequencies.

K. Maischberger, Bruno Bertotti and G. Fiocco are operating a detector at 1661 Hz—almost identical to Weber's—at ESRIN in Frascati, Italy. The data are transferred to magnetic tape every tenth of a second, and the output is analyzed and compared to thermal noise.

Hans Billing is operating an almost identical detector at the Max Planck Institute in Munich, in collaboration with the Frascati group, and their first fragmentary results from a few days' running indicate no events corresponding to the type Weber has seen, at a sensitivity comparable to that reported by Weber in 1969.[30] The experiment is presently operating, and data for a significant comparison should be available in a few months.

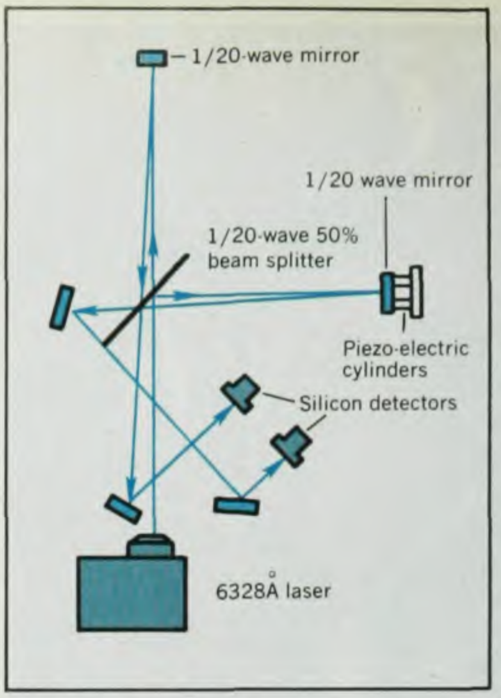
The data are recorded in a standard format on tape, so it is hoped that a correlation experiment with Weber, and with other groups, can be run.

Peter Aplin, at the University of Bristol in England, is constructing a detector of the special design described earlier (see the discussion of Drever's system), which should have sensitivity comparable to Weber's and excellent time resolution. Douglas Allen, at the University of Reading in England, is also building such an apparatus.

William Fairbank at Stanford University and William Hamilton at Louisiana State University in Baton Rouge are preparing an experiment with 12 000-pound, 3-ft × 10-ft cylinders cooled to millidegree temperatures and suspended by superconducting magnets.[40] These groups hope to run in collaboration with Edoardo Amaldi, Guido Pizzella and Giorgio Careri at the University of Rome, who plan to use a 5-ton aluminum bar cooled to less than 0.1 K with a superconducting strain transducer to detect bar vibrations of 10^{-17} cm. When these systems are perfected, which could take several years, design sensitivities more than 1000 times those currently possible should be achieved.

G. Papini and E. Tward at the University of Saskatchewan in Regina are building a 0.01 K cryogenic system based on a quartz cylinder that has a design sensitivity of the same order as Weber's experiments.

In addition to his cylinder detector, Douglass, at the University of Rochester, is developing a mass-quadrupole resonant antenna of the Weber type but of hollow-square geometry. Such a detector can be designed for sensitivities in the 30–1000-Hz region comparable to that of cylindrical antennas at higher frequencies. (For cylindrical antennas, $\omega_0 \approx l^{-1}$, whereas for the geometries of what Douglass calls "Class II detectors" $\omega_0 \approx l^{-2}$, where ω_0 is the resonant frequency and l is the length.)[41] Detectors of this type are sensitive also to scalar radiation in certain modes, and they are also convenient for polarization measurements. At such low frequencies one could hope to look for the 60.44-Hz radiation expected from the pulsar in the Crab Nebula.[42,43]



Layout of the Michelson interferometer used in the broadband (nonresonant) radiation detector of Forward and Moss. Radiation incident along the laser axis would produce fluctuations in the lateral optical path length, but not in the longitudinal path to which it is compared. In the present operating configuration, the light path is folded by multiple reflections. (The piezo-electric cylinders are driven to produce vibrations in order to calibrate the system response.) Figure 6

Seismic experiments

The Earth has a significant mass-quadrupole mode with a period of 54 minutes (and also higher-frequency modes, of course), and Weber,[3] and later Dyson[29] and others, suggested instrumenting the earth as a gravitational radiation detector by studying the signals from sensitive vertical seismometers. Weber and Jerome Larsen[7] reported such a study in 1966, and Weber deduced a limit $\rho < 8 \times 10^{-31}$ g/cm^3 for the mass-density of gravitational radiation at that frequency in the universe (of the same order as the critical density required to "close the universe") based on these observations. Unfortunately it is probably not possible to increase the sensitivity of such observations to a more significant level because of the degree of seismic noise that is always present on the Earth.

The moon is considerably less noisy, and Weber was the first to propose instrumenting the moon as a detector. The Apollo 17 astronauts recently installed on the moon a gravimeter, designed by Weber, Jean-Paul Richard, Larsen, and John Giganti, which is sensitive in three modes: a 1–16-Hz channel, a 1 cycle per 20 minutes to 1 cycle per minute channel (sensitive at the main lunar quadrupole-mode period of 15 min), and a channel sensitive down to dc, sensitive to the two-week tidal effects. The two high-frequency channels are sending data back to earth, and by June Weber hopes to have a significant portion analyzed for possible evidence of gravitational radiation (and for significant information about the moon!).

Precision timing of laser pulses from the Earth, returned by corner reflectors placed on the moon in a previous lunar mission, could also provide such information in principle by measuring fluctuations in the Earth–moon distance. That experiment is, however, not sufficiently precise to be useful for plausible radiation fluxes; nevertheless, other tests of general relativity may be possible with the system.

Recently D. Sadeh and M. Meidav reported[44] an analysis of seismic data from a vertical seismometer in Israel sensitive in the 0.1–10-Hz region. They searched for, and found, a large Fourier component corresponding, to four decimal places, to twice the frequency of pulsar CP 1133. Sadeh also reported[45] a correlation in the activity of the vertical seismometer installed on the moon during the Apollo 12 mission with the pulsar. However, a careful analysis of seismic data by T. S. Mast and others.[46] with superior precision failed to find such a signal in data obtained from a seismometer in the Sierra Nevada.

Ralph Wiggins and Frank Press have searched for signals synchronous with four nearby pulsars with negative results, and presently Mast, J. E. Nelson and J. Saarloos are searching existing seismic data for correlations with all known pulsars, so far with completely negative results.

Some proposals

Braginskii[19] has proposed a "crossed dumbell" quadrupole heterodyne experiment. Two perpendicular mass quadrupoles would be attached to axles rotating with velocity ω; a gravitational wave of frequency 2ω incident along the common axle direction would produce "beats" in the rotation frequency, fluctuations in the relative phase of the bars, that one could try to observe. He believes a laboratory-sized receiver of this type could be adequate to observe the expected radiation from the pulsar

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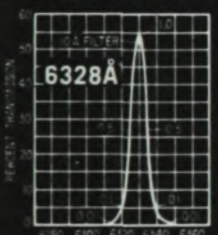

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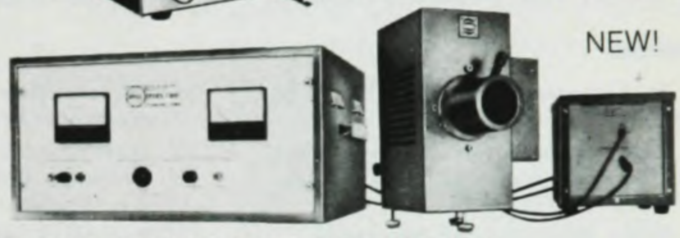

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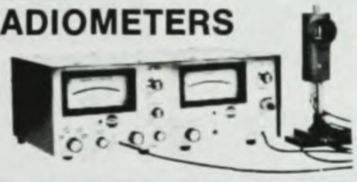

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in the Crab Nebula.

Braginskii and M. B. Menskii[47] have proposed a "gravitational-electromagnetic resonance" experiment based on an annular waveguide with circulating electromagnetic radiation. The phase difference at two points $\pi/2$ apart would fluctuate with an amplitude depending on the cumulative energy flux transferred by gravitational waves incident in the direction normal to the annulus plane. The device would be extremely sensitive but only (unfortunately!) at frequencies corresponding to the electromagnetic (microwave) frequencies, that is, in the MHz region.

Some other interesting detection schemes have recently been proposed; see especially references 37 and 48.

Dyson has compared the present situation to the earliest days of radioastronomy.[29] Radioastronomy, we have recently been reminded,[22] was invented in 1932 by Karl Jansky, a radio engineer, in the process of some noise measurements he was assigned to make to determine the direction of arrival of thunderstorm static, which interferes with radiotelephone communication.

Jansky identified and reported "... a steady hiss type static of unknown origin ... a hiss in the phones that can hardly be distinguished from the hiss caused by set noise."[49] There was a 24-hour variation in the intensity of this hiss, and Jansky first guessed that it was connected with the sun. In the following year, he determined that the strongest signal came from a direction fixed in space, a region of the sky including the center of the galaxy.[50] It turned out that he was right.

In this century "Astronomy" has become radioastronomy, microwave astronomy, infrared astronomy, ultraviolet, x ray, and gamma-ray astronomy, (and optical astronomy!), and cosmic-ray astronomy in its own right.

The sensitivity and resolution of the gravitational radiation detectors can be improved by enormous factors. Laboratory-sized detectors of Weber's original design, but cryogenically cooled and with more sophisticated detection schemes, can achieve sensitivities a million times greater. It will be possible to move the experiments into space, where it is very cool and very quiet; new experiments will be designed, and an international network of receivers can be run as a phased array. Other possibilities exist. With any luck we will have a gravitational-radiation astronomy too—the prospect is dazzling.

* * *

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