Getting Ready for LIGO

The Detection of Gravitational Waves. DAVID G. BLAIR, Ed. Cambridge University Press, New York, 1991. xxiv, 481 pp., illus. $135.

To a theoretical physicist, there is a deep analogy between electromagnetic waves (such as light or radio waves) and gravitational waves, a phenomenon associated with the force of gravity. From a practical standpoint, however, the two sorts of waves are worlds apart.

On the basis of his unification of electric and magnetic forces, James Clerk Maxwell predicted in 1864 that disturbances in the electromagnetic field would propagate as waves, traveling at the speed of light. Almost a quarter of a century elapsed before Heinrich Hertz succeeded in carrying out the experiments that conclusively demonstrated the existence and nature of electromagnetic waves. This work earned Hertz the special prize that had been offered by the Prussian Academy of Science.

In the ensuing years, electromagnetic waves transformed the world by their application to wireless communication. During World War II, electromagnetic technology played a crucial role in the Allied victory through the development of radar. A remarkable array of talent was brought together in the Radiation Laboratory at MIT. In a few short years, the Rad Lab team thoroughly mastered the technology of microwaves and produced practical radar sets that helped guarantee Allied air supremacy.

Before disbanding after the war, some of the key workers at the Rad Lab recorded what they had learned in a series of 26 volumes, each devoted to a particular branch of microwave technology. The Rad Lab series remained a standard reference for many years; though some of the books on specialized components were soon rendered obsolete, a number, among them Montgomery, Dicke, and Purcell's *Principles of Microwave Circuits* and Silver's *Microwave Antenna Theory and Design*, were true classics.

History has moved more slowly in the case of gravitational waves. Their existence was first predicted by Einstein in 1918 as one of the most distinctive consequences of his theory of gravity, the General Theory of Relativity. But no prize was offered for their detection; Einstein's belief that gravitational waves would be too weak ever to be detected was widely shared.

That belief was challenged in the 1960s by Joseph Weber. Inspired perhaps by the successes the Rad Lab alumni and their colleagues had had in creating the new field of radio astronomy, as well as the parallel achievements of others in exploiting the remaining bands of the electromagnetic spectrum, Weber began to build detectors for gravitational waves of cosmic origin. Mimicking Hertz's strategy of constructing a transmitter is ruled out by the feebleness of gravity. But the newly discovered pulsars (rotating neutron stars), the enigmatic quasars, and the tantalizing possibility of black holes gave reason to hope that the universe might provide a strong enough source of gravitational waves, even across astronomical distances. If this should prove to be true, then yet another new window on the universe would be opened.

Weber's 1969 report that his resonant aluminum bars had been set into vibration by gravitational waves of cosmic origin set the world of astrophysics aquiver as well. By the early 1970s, several attempts had been made to duplicate his results, all without success. This outcome was greeted by most scientists with a mixture of disappointment and relief, for to be seen by detectors of the then-achievable sensitivity the sources would have required astounding luminosities. (Weber himself has never accepted the conclusion that his results were spurious.)

In spite of these dashed hopes, a number of other physicists were inspired to carry on the quest, building detectors of ever-increasing sensitivity. Resonant bars of Weber's style were cooled to very low temperatures and outfitted with low-noise superconducting sensors. Laser-illuminated Michelson interferometers have been built to sense tiny motions of test masses up to 40 meters apart. Radio transponders on interplanetary probes have been pressed into service, as have the serendipitously provided radio signals from the rock-steady rotation of pulsars. Technological progress has not been as rapid as in the days of the Rad Lab, but dramatic improvement in sensitivity has been achieved. A detection of gravitational waves would no longer be a surprise.

Now we are, it is hoped, at a turning point in this long quest. When the U.S. budget for fiscal year 1992 was signed into law, it contained funds to begin the construction of the Laser Interferometer Gravitational Wave Observatory, or LIGO. This is to be a pair of advanced interferometric detector facilities with arms 4 kilometers in length, installed at widely separated sites in the United States. Its builders, physicists from Caltech and MIT (the latter housed in one of the original Rad Lab buildings), predict that it will have sufficient sensitivity to make detection of cosmic gravitational waves not only possible but likely. Plans are nearing fruition for similar facilities in Europe; Japanese physicists have also announced their intention to follow suit.

So it is an appropriate moment to consider the state of this field. David Blair of the University of Western Australia, a long-time developer of the cryogenic Weber-style detectors, has provided a very valuable survey in a volume hopefully entitled *The Detection of Gravitational Waves*. Four of the book's 17 chapters list Blair as either author or coauthor; for the rest, he has assembled contributors from most of the leading research groups around the world. Together these chapters give a fairly complete description of the state of the art of constructing gravitational wave detectors of all varieties.

There is much of value here, some of it difficult to find in print elsewhere. The introductory chapters by Blair on the physics of the waves and of their sources are brief, but they contain a number of unusual insights. The majority of the book's chapters focus on specific technical topics, almost as if they were small volumes in a Gravitational Rad Lab series. Part 2 of the book, on resonant-bar detectors, consists of several chapters containing much beautiful experimental physics knowledge and engineering lore. Among the topics authoritatively discussed are dewars, motion transducers, and data analysis. Laser interferometers are dealt with in detail in part 3. Included there are an admirable discussion of laser stabilization, a complete description of the optical techniques known as "recycling" and "squeezing," and an insightful summary of how to analyze the mountains of data that will be recorded. The book concludes with a fine chapter on detection techniques based on experiments involving spacecraft and the timing of signals from pulsars.

In some ways the editor could have done a better job of ensuring balance. The chapter on vibration isolation for interferometers is marvelously lucid but too brief to contain much detail. There is also a beautiful review, at some length, of the theory of internal friction in materials, but its discussion of gravitational wave applications is limited to resonant bars, and even there almost exclusively to the properties of niobium. There is virtually no discussion of the history of the field, and, with the exception of the chapter on space experiments, no discussion of the scientific results (alas only upper limits on wave strengths) that have been obtained to date.

Readers from outside the field will have trouble obtaining a clear sense of the state of this field from the book. The overview chapters seem too sketchy for the purpose, and the book as a whole has the air of documenting a mature field rather than alerting newcomers to the potential of one that is dynamic and rapidly evolving. Perhaps the biggest lack is a coherent summary of all the factors that lead the scientists in the field to believe that successful detection of gravitational waves will come soon. (It would have been helpful to discuss the sensitivity of the best present-day detectors.) The case for LIGO and its cousins has to be pieced together from many chapters.

For those active in the field, the volume addresses an unmet need. Unlike the authors of the Rad Lab series, we cannot yet look back on how we successfully met the challenge of detecting the waves we are looking for. But with perseverence and luck, that day should come soon.

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A Slice of the Brain

Neuronal Networks of the Hippocampus. ROGER D. TRAUB and RICHARD MILES. Cambridge University Press, New York, 1991. xviii, 281 pp., illus. $39.50.

The experimental study of the neuronal networks underlying sensory perception, motor control, memory, and cognition has recently begun to advance beyond the data-driven phase in which phenomena are described and categorized ever more finely but without unifying and quantitative theories to a more mature, quantitative stage. The last few years have witnessed increasing use of methods from mathematical physics to study aspects of the nervous system as well as a dramatic growth in detailed computer modeling. These trends are embodied in *Neuronal Networks of the Hippocampus.*

The primary aim of the work reported is to understand from first principles one of the neuronal networks making up the mammalian hippocampus, part of the cortical system known to play a crucial role in the formation of episodic memory traces. This part of the brain, encompassing on the order of 10 million nerve cells in the human, is also particularly susceptible to epileptic seizures, with unfortunate consequences. In the celebrated case of H.M., intractable epilepsy led his doctors to remove the medial temporal lobe (which includes the hippocampus) on both sides, rendering him forever incapable of remembering for more than 1 or 2 minutes events that happened after the operation. His "procedural" or "habit" memory system is, however, not impaired (thus, he can learn how to solve the "Tower of Hanoi" without recalling ever having seen this puzzle before).

Though it has been popular to study epilepsy experimentally by recording in vitro from slices from a particular part of the hippocampus called CA3, Traub and Miles (and their collaborators, in particular Bob Wong) are unique in combining these investigations with large-scale realistic network simulations. The results of this exemplary interaction between experiment and computer model are described here.

The book is organized into three parts. The first three chapters introduce the hippocampus, the physiology of its two main types of neurons, and their synaptic connectivity. The authors focus on various collective population phenomena in which large assemblages of neurons fire simultaneously. Such synchronized activities include rhythmical EEG waves in the theta range (4 to 12 Hz), sharp waves and EEG spikes (short electrical events that reflect a limited degree of synchronized cell firing), and various types of epileptic seizures. The second part of the monograph describes in great detail the authors' computer model. They adopt the heroic position that understanding neuronal networks requires creating as close as possible a one-to-one copy of the system in the computer. Thus, they numerically simulate 9000 excitatory and 900 inhibitory cells (out of about 20,000 making up the CA3 slice preparation). The dendritic tree of each cell is approximated by a number of spatially discrete compartments containing voltage-dependent sodium, potassium, and calcium currents; individual cells can reproduce the various voltage trajectories observed experimentally, in particular isolated action potentials and bursts (a small group of tightly clustered spikes). The network topology mimics the known anatomy of the CA3 area: local random connections whose density decreases exponentially with distance. This section of the book also includes all the relevant equations and details of the computer program.

The crucial test of any model is its ability to make new predictions, and the heart of the book is in the third section, where the model reproduces the propagating waves and other synchronized events seen both in slice and in the intact animal when inhibition is reduced or blocked by various pharmacological agents. By the standard of the field, this model does quite well, having predicted that a burst in a single pyramidal cell can evoke a burst in another pyramidal cell and that stimulation of a single neuron can frequently evoke synchronous firing, lasting 50 to 100 milliseconds, in a large population of disinhibited CA3 cells. Both phenomena have subsequently been verified experimentally. The latter one is particularly intriguing, since it is a genuine collective phenomenon. In order for each neuron in a large network with random connectivity to fire—through the building up of a chain reaction among excitatory pyramidal cells—it is known both experimentally and theoretically that 1000 to 2000 hippocampal neurons are required. In other words, a "critical" number of neurons has to exist (as well as a minimal excitatory synaptic strength). If the network is spatially elongated, a wave of neurons bursting simultaneously moves slowly across the slice. The finite propagation velocity is due to the spatially decaying synaptic connectivity among neurons.

One chapter deals exclusively with field effects among neurons, mediated by extracellular potential gradients. Such effects are expected to be significant in the hippocampus, with its regular geometry and tight neuronal packing density. Experiments and computer modeling show that they can act as a weak but global synchronizing mechanism among neurons, compared to the sparse but powerful point-to-point interaction mediated by synapses. Finally, Traub and Miles discuss how various concepts from the theory of dynamical systems (chaos, embedding dimension, strange attractor) as well as Hopfield and connectionist neural networks and percolation theory (the study of transmission among randomly interconnected nodes in an evolving network) may be relevant for understanding the structure and function of the hippocampus.

The book integrates experiments and computer modeling into a seamless fabric, something still rare in the neurosciences. The use of arguments from statistical physics and dynamical systems theory is compelling and to the point. The monograph should be required reading for any researcher seriously interested in networks of complicated and highly interconnected neurons, in particular for those of us reasoning about models of synchronized "40 Hz" oscillations observed in mammalian cortex. The novice should be warned, however; many important concepts