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Editorial Note to: Electromagnetically Coupled Broadband Gravitational Antenna

by Rainer Weiss

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Abstract

Rainer Weiss' 'Electromagnetically Coupled Broadband Gravitational Antenna',* published in the MIT Research Laboratory of Electronics Quarterly Progress Report, triggered a new field of science. On its 50th anniversary, the article is being republished in the general literature. We offer a short introduction to put it in context.

Keywords: Interferometry, Gravitational-wave detectors, History, Experimental design

In 1972, Rainer Weiss published in the *Quarterly Progress Report of the MIT Research Laboratory of Electronics* an assessment of an idea on which he had been working for several years to use laser interferometry to detect gravitational waves. This unassuming report ('Electromagnetically Coupled Broadband Gravitational Antenna', QPR in the following) established the path for the now-burgeoning field of the observation of the gravitational-wave strain due to astrophysical sources, giving direct evidence to date of the accuracy of general relativity in the most extreme conditions and the the existence of stellar black holes [1], the speed of propagation of the waves and tests

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[*] The republication of the original article can be found in this issue at https://doi.org/...

of GR [2], and (with electromagnetic detection) establishing multi-messenger astrophysics with gravitational waves as a tool to understand binary neutron star mergers [3].

Weiss had been interested in this topic since his days as a postdoc at Princeton in the early 1960s with Robert Dicke, when he helped design an experiment to look at the excitation of earth normal modes due to passing gravitational waves. Taking up a faculty position at MIT, he found himself teaching general relativity and learning it on the fly as he prepared lectures. Weiss wanted to find a way to realize the conceptual vision for the students of using light travel times to sense the strain in space due to a passing gravitational wave (an approach hinted at in Pirani's paper on the concept of gravitational-wave detection [4, 5]), and set up a homework problem in the later 1960s involving a Michelson interferometer using a then-novel laser as the light source. This approach was based on other work in Weiss' lab at the time, so that the technical feasibility in principle was already evident to Weiss. Once the germ of the idea was established, Weiss and some of his close collaborators of the time fleshed out the idea and started to look at some of the practical questions of implementation. After several years of gestation, Weiss gathered the considerations in this seminal paper written as part of the reporting required for the funding that seeded it.

The idea was developed at the time that Joseph Weber was developing and using mechanical resonators – 'acoustic bar detectors' – to try to capture the signal from a passing gravitational wave. Weiss' concept had a number of significant advantages over this approach: the ability to enlarge the length over which the strain is sensed (increasing the signal size), and offering a broad frequency sensitivity such that the waveform could be captured – not just an amount of power in a limited band. Others had either considered in the abstract the interest of monitoring free particles [5], had sketched the use of interferometry [6], or in fact pursued the construction of small prototype detectors [7], but Weiss' effort appears to have been developed initially independently in the context of his need to teach general relativity and his familiarity with the tools of precision laser interferometry.

The QPR has served as both an introductory text for students and a roadmap for the development of the field since it appeared. Its structure – a conceptual design followed by a litany of limitations to sensitivity and scaling laws – was probably stimulated by Dicke's approach to experimental design [8], and served to structure much of the 40-some years of research that carried the concept to fruition as the Advanced LIGO detectors (e.g., [9])

The QPR is remarkably complete and still correct in most details on the physics of the detectors and the means to achieve the needed sensitivity. Thermal noise has been refined with better models for loss mechanisms in real materials [10] and with the realization that mirror coatings are a dominant source of noise [11], but the concepts are correct here. Seismic noise and gravitational gradient forces are accounted for. Photon shot noise is correctly portrayed as a key 'fundamental' limitation along with the practical need for frequency (or phase) stabilization; the radiation pressure noise is one place where Weiss did not foresee the consequences of the statistical splitting of light at the beamsplitter (which was recognized and greatly generalized in 1980 by Caves [12]). Coupling of the radiation pressure to the light phase [13], and to optics mechanical modes [14], only surfaced as complications relatively recently. Other more practical technical concerns, such as stray electric and magnetic fields, have remained a driver for all the current and future detector designs. Missing from the QPR is the practical importance of scattered light [15], and while the quality of the vacuum required around the optics is estimated to limit thermal noise, the quality of vacuum for the ∼ km laser beam path to avoid light path fluctuations was not addressed [16].

In addition to the accounting for the various noise sources, Weiss proposed several key design concepts that have been crucial to the ultimate success of these detectors: the use of servocontrols to hold the detector at the correct operating point, and the use of null servos to minimize noise couplings; the use of pendulums to seismically isolate the interferometer mirrors from external forces; and the use of low-internal-mechanical loss ('high Q') materials to gather thermal noise into narrow bands all define the approach for all of today's – and tomorrow's [17, 18] – terrestrial gravitational-wave detectors. Weiss also proposes 'folding' the interferometer arms to make a better impedance match of the ∼km long arms with the ∼ 100 km long gravitational waves. Weiss' approach – the Herriot delay line – was used for some successful prototype demonstrations, but ultimately practical considerations led to the adoption of Fabry-Perot cavities for this purpose. Of course significant advances in interferometer 'topology' have been made in the interim [19], but these can, to date, be seen as more elaborate realizations of the Michelson interferometer that Weiss proposed.

The QPR paper still is fresh and remarkably clear on the concepts, and still bears reading after 50 years not only for the physics and design content, but for the vision which is so clearly communicated.

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Rainer ("Rai") Weiss: a brief biography

by M.A.H. MacCallum

Prof. Rai Weiss has been one of the principal progenitors of two major (perhaps *the two major*) developments in observational astronomy and cosmology in the last half century. As well as the seminal paper on gravitational wave observations republished herewith, he played a leading role in the COBE (Cosmic Background Explorer) mission which produced the first measurements of the anisotropies in the cosmic microwave background (CMB). He is now Emeritus Professor of Physics in the Kavli Institute for Astrophysics and Space Research in the Massachusetts Institue of Technology (MIT).

Weiss was born on September 29, 1932, to a Jewish doctor father, Frederick A. Weiss, who became a psychoanalyst, and a Protestant mother, Gertrude Loesner, with ambitions to act, in Berlin. His father, being both Jewish and communist, inevitably had problems with the Nazis: Weiss' mother's family helped get him released after he was made prisoner by a Nazi gang, and the Weisses moved to Prague. Then in 1938, as one of the many trying to escape after Hitler took control of the Sudentenland, the family were fortunate to be among those gaining the support of the Stix family of St. Louis to emigrate to the USA in 1939.

Weiss obtained a scholarship to the Columbia Grammar School in New York. While there he developed an interest in electronics, leading to a successful small business making hi-fi equipment. This led to a interest in noise reduction, a serious problem with the technology of the day. It was for that reason that when he entered MIT in 1950, it was in electrical engineering, but he switched to physics because the programme did not cover electronics.

Soon an unhappy romantic experience led to him failing his courses. His electronics expertise enabled him to become an electronics technician at MIT working under Jerrold Zacharias. It has been reported he first walked into Zacharias' lab and started carpentry there, making a dry ice chest. Zacharias' purpose was development of the Caesium beam atomic clock, aiming to achieve precision sufficient to measure gravitational redshift. Sadly the design ran into trouble for reasons Weiss identified by experiment, later resolved in today's laser-cooled designs. Weiss also worked on other ideas for better clocks and on a Mössbauer experiment related to a theoretical explanation of cosmic redshifts.

While at Zacharias' laboratory Weiss completed his undergraduate degree (S.B. 1955) and started graduate work on clocks. Under pressure to complete because his wife Rebecca had become pregnant, he then "did a boring but useful measurement of the electric dipole moment of HF" [hydrogen fluoride] to finish his Ph.D. (1962) and obtained an instructor's position (soon raised to assistant professorship) at Tufts University (1960–62). He was to be promoted to Associate Professor, but wanted to work with Robert Dicke at Princeton, and did so as a Research Associate in 1962–64. During that time, some important experiments in gravity were carried out and others proposed (see [20]). Weiss was involved in an idea to measure scalar gravitational waves, prompted by the Brans–Dicke theory, using a gravimeter, an experiment which was limited by geophysical excitations, but which stimulated an interest in gravitational wave detection. Weiss wrote of this period that "The critical and lasting knowledge was how one designs an experiment to get to its fundamental limits. Dicke was a master at this."

In 1964 Zacharias invited Weiss back to MIT as a faculty member, where he was promoted to Associate Professor in 1967 and full Professor in 1973, moving to Emeritus status in 2001. He started a new laboratory dedicated to

Cosmology and Gravitation, beginning with a plan to check the time variation of the gravitational constant G. This involved kilometer long laser strain gauges, the noise properties of lasers and a tabletop Michelson interferometer. The next year Weiss was asked to give the first MIT graduate course on relativity and felt obliged to do so in view of his laboratory's aims.

The lectures included the cosmological application and Weiss started to think about checking the Planck spectrum of the cosmic microwave background. His head of division, the radio astronomer Bernard Burke, suggested he move to doing that as his main objective, as "more likely to lead to interesting results soon enough for decisions ... in the department". With colleagues he developed the technology for a series of balloon flights, which succeeded in checking the spectrum but "not with much precision". His attention then switched to satellite experiments on the CMB, initially to measure the dipole contribution to the distribution.

John Mather had conceived the COBE mission and recruited Weiss to join it, Weiss becoming the chair of the 18 strong Science Working Group (see his contribution to [21]). COBE, launched in 1989, showed, in a series of papers from 1990 onwards, that the early universe was hot, dense and contained the weak fluctuations or lumps that grew into today's galaxies and stars, evidence for which from the later WMAP and Planck experiments has led to very precise values for the parameters of the standard cosmological model. In 2006 Mather won half of the Gruber Prize for Cosmology for this work, the other half going to the team headed by Weiss, and in the same year Mather and George Smoot won the 2006 Nobel Physics prize.

In 1969 Joseph Weber announced he had observed gravitational waves using his bar detector technique, and Weiss' students asked him to explain. Although Weiss thought the CMB work was simpler, he then generated ideas for a gedanken experiment measuring a one-dimensional length variation due to waves. This and his earlier experience with laser frequency stabilization and noise characterization led to the gedanken experiment becoming a real experiment, based on the ideas in the paper republished here.

At that point Weiss was a member of the MIT Research Laboratory of Electronics, which was supported by funding from the US military. He obtained military funding to build a 1.5-m prototype based on his paper, but that soon after ceased for political reasons. Other funders, and MIT itself, were not very sympathetic to supporting that line of work. With better funding, more progress on the same lines was being made by the group at the Garching Max Planck Institute and by Ron Drever's Glasgow group. When Weiss met Kip Thorne of Caltech (the California Institute of Technology) in 1975 it led to the crucial co-operation of MIT and Caltech that became LIGO. In his Nobel prize lecture [22] Weiss describes this phase which eventually led to the direct detection of the waves announced in 2016.

By 1992 the work had advanced to the point where Drever, Thorne and Weiss successfully proposed the building of LIGO itself to NSF. In the webcast in early 2016 announcing the first detection of gravitational waves, this was said to be the largest grant NSF had made up to that date. In 2007 Weiss and Drever were awarded the American Physical Society's Einstein Prize, which is for outstanding accomplishments in the field of gravitational physics. But it was not until Advanced LIGO was up and running in 2015 that the first signal, from colliding black holes, was seen, as was announced on February 11, 2016.

Apart from his own direct research contributions, the positive and supportive ethos he established within his research group made it a very pleasant place to work, and facilitated the training and nurturing of many of the most important contributors to the two fields of CMB and gravitational waves: to mention just a few, Bruce Allen, Nergis Mavalvala, Lyman Page, and David Shoemaker.

Over the years Weiss has served the US science community as a member or chair of numerous NASA and other committees, panels, review bodies and task forces. As well as his atomic clock work he is known for his invention (with 6 co-authors) of monolithic silicon bolometers, first described in published work in 1980. But his most influential work will undoubtedly be the 1972 paper reprinted here and the experimental work that flowed from it.

As well as the Gruber prize for the COBE work, and the APS Einstein Prize, Weiss has won numerous awards, together with co-workers, for the gravitational waves work, among them a 2016 Special Breakthrough Prize, a 2017 Gruber Prize, the Shaw Prize, the Kavli prize and the 2017 Nobel Prize in Physics (half going to Weiss and the other half shared by Kip Thorne and Barry Barish).

Acknowledgements. This biography has been taken from several online sources, which give much more detailed information than could be included here. In particular, they give much fascinating additional background to Weiss's various experiments and the development of his experience and knowledge. They include Weiss' Wikipedia entry, the biography accompanying his Nobel Prize award [23]. his Nobel prize lecture [22], and a recent press interview [24]..

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