doi: https://doi.org/10.15407/knit2017.03.047
UDC 530.12:531.51

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HIGH-FREQUENCY GRAVITATIONAL WAVE RESEARCH AND APPLICATION TO EXOPLANET STUDIES

A discussion of the history of High-Frequency Gravitational Wave (HFGW) research is first presented. Over the years until modern times, starting with the first mention of Gravitational Waves by Poincaré in 1905 and the definition of HFGWs in 1961 by Robert L. Forward, the discussion continues concerning the international research efforts to detect HFGWs. The article highlights the accomplishments of HFGW researchers in China, Russia, Ukraine, England, Australia, Japan, Germany, Spain, Italy, and the United States. Comparisons are made with Low-Frequency Gravitational Wave (LFGW) research, especially concerning the Laser Interferometer Gravitational Observatory or LIGO. In fine, there are presented several interesting perspectives concerning cosmology, the speed of time and, especially, exoplanet applications of HFGWs.

Keywords: *gravitational waves, high-frequency gravitational waves, HFGWs, HFGW Detectors, speed of time, exoplanets, LIGO, Starshot.*

INTRODUCTION

If we swim in the ocean we feel the water waves. When we listen to a song we hear acoustical waves. When we look at each other we see the light or electromagnetic waves. But are there other possibly invisible waves not so easily sensed?

It was in 1905, several weeks before Einstein presented his Special Theory of Relativity that Henri Poincaré, the famous French mathematician and Celestial Mechanic, suggested that Newton's theories needed to be modified by including ”Gravitational Waves” [1]. However, Poincaré, presented little or no specific analyses.

In 1916 such Gravitational Waves (GW) were first mathematically analyzed in the paper authored by Albert Einstein, where he discussed Gravitational Waves in his theory of General Relativity [2]. Specifically, in 1918 Einstein derived the quadrupole formula or equation [3] according to which Gravitational Waves are produced in his newly studied ***space-time continuum*** by a time-dependent mass quadrupole moment (literally a four-pole moment, actually a 4 × 4 tensor; as pointed out in an overview of gravitational radiation prepared by the Astronomy Department of the University of Maryland, there cannot be monopolar gravitational radiation, there is no dipolar gravitational radiation either, but there can be quadrupolar gravitational radiation). The quadrupole moment showed that Gravitational Waves can carry energy. Also the quadrupole wave is the simplest solution that maintains conservation of momentum during the propagation of the wave [4].

In 1936 Einstein submitted, together with Nathan Rosen, a manuscript to the “Physical Review” in which they claim that gravitational waves do not exist. In 1937, after receiving a critical referee report,

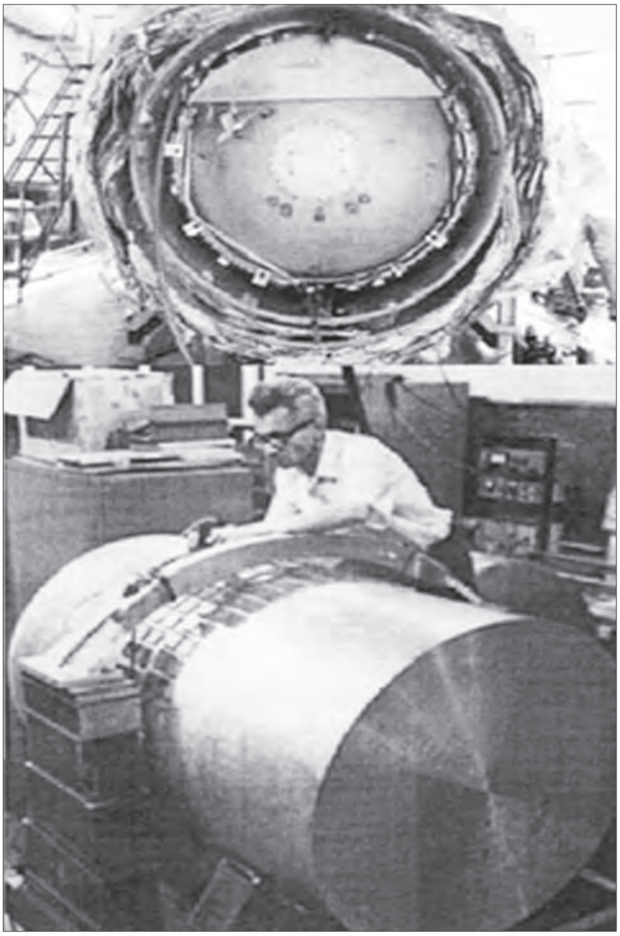

Fig. 1. Joseph Weber and his "Weber Bar"

Einstein was upset and withdrew the manuscript (with the erroneous claim) and published, again together with Rosen, a strongly revised manuscript confirming Gravitational-Wave solutions in the "Journal of the Franklin Institute" [5]. (Rosen actually departed for Moscow just before the actual publication [6].)

After reviewing the early work of Einstein, Joseph Weber suggested the detection of Gravitational Waves utilizing a large 2,400 pound Aluminum cylinder that, when isolated from all external vibrations, would resonate like a "bell" excited by incoming Gravitational Waves – his so-called "Weber Bar" (Fig. 1). His results were inconclusive and resulted in some reports that are still debatable. It is worth noting, however, that a Weber-Bar type detector of Gravitational Waves was developed at the Institute of Theoretical Physics in Kiev in the late 1970s. At the end of 1970s Aleksey Zinovievich Petrov, who worked at the Institute for Theoretical Physics of the Academy of Sciences of the UkrSSR (hereafter — ITP), has initiated the work on the creation of a unique device — the Weber type antenna — for monitoring of Gravitational Waves from powerful extragalactic sources. Being a physicist-theorist, he was aware of the need for an experimental confirmation of the main principles of the General Relativity. A premature death of A. Z. Petrov made significant adjustments to the plans for theoretical and experimental gravitational studies in Ukraine. In particular, part of his followers moved to the Ukrainian Center for Standardization and Metrology of the State Committee of Statistics of the USSR. General management of works was carried out by K. A. Piragas, while a principal development of "Weber Bar" in Kiev was guided by A. M. Sviridov. This group included such Ukrainian physicists as V. I. Kopylov, S. S. Zhovnir, I. T. Zhuk, Yu. A. Opanasyuk, A.N. Alexandrov, and others. They had spent a lot of time in attempts to detect Gravitational Waves using the constructed Weber Bar [82, 87].

Research and Detectors of Gravitational Waves. The first mention of High-Frequency Gravitational Waves (or HFGWs) that I could determine was in a meeting in 1961 that I had with Dr. Robert Lull Forward at my Lockheed Astrodynamics Research Center in Bel Air, California[1]. I had invited him over from the Hughes Research Laboratory in Malibu, California, to deliver a lecture on the "Weber Bar" that he and Dr. Joseph Weber were constructing at the Hughes Lab to detect Low-Frequency Gravitational Waves (1660 Hz). During the Question and Answer part of our Lecture, Bob Forward and I talked about building a Laboratory generator and detector for "High-Frequency Gravitational Waves", hav-

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[1] Lecture was given at the Lockheed Astrodynamics Research Center (LARC), 650 N. Sepulveda, Bel Air, California, USA, a few blocks from UCLA, November 16th, 1961. A Lockheed Research Report RL 15210 was published based upon notes taken by Samuel Herrick, a Lockheed Consultant and UCLA Professor. Attendees included LARC members Robert Rector, Professors Geza Gedeon, Kurt Forester, my secretary Joan Boyle (who typed up Herrick's notes in the Lockheed Research Report of the Lecture), plus UCLA students.

ing frequencies over 100 kHz. As far as I know this was the first time the subject had been broached. I recall that we concluded that it could not be accomplished with the technology then available; but I suggested that such high-frequency gravitational waves, or HFGWs, might be useful in the study of the early Universe and would have practical applications, for example, communication (the ultimate wireless system). They would be useful for the interception of interstellar communications by extraterrestrial advanced civilizations, whose communications means of choice would be high-frequency gravitational waves since, unlike electromagnetic radiation, HFGWs pass un-attenuated through all matter including interstellar matter [7, 8].

There were no actual scientific or technical publications concerning High-Frequency Gravitational Waves that I could find until mid-1962, when Mikhail Gertsenshtein authored the pioneering paper entitled "Wave resonance of light and gravitational waves" [9]. The Gravitational-Wave frequencies being about those of light ($4 \cdot 10^{14}$ Hz is red light, $8 \cdot 10^{14}$ Hz is violet light) would be considered HFGWs. Unfortunately, the Gertsenshtein effect is so weak that it has no value for the detection, generation or applications of HFGWs. By the way, the idea that laid the theoretical basis for, or a precursor of, future big Gravitational-Wave interferometers, such as the Laser Interferometer Gravitational Observatory for the detection of Low-Frequency Gravitational Waves (LFGWs), was put forward by Gertsenshtein and another Russian scientist Vladislav Pustovoit in 1962 and reported on in 1963 [10].

In 1967 Rainer Weiss from the Massachusetts Institute of Technology published an analysis of interferometer use for LFGW detection and initiated the construction of a prototype with US military funding. Unfortunately, the construction was terminated before the laser LFGW detector could become operational. The concept eventually was utilized in the Laser Interferometer Gravitational-wave Observatory or LIGO [11].

The next publication concerning HFGWs was in August of 1964, when Leopold Ernst Halpern and Bertel Laurent wrote a paper in "Il Nuovo Cimento" [12]. Like I had in 1961, they suggested that "*...at some earlier stage of development of the Universe (the Big Bang) were suitable to produce strong (relic) gravitational radiation*" [12, p. 729]. They then discuss "short wavelength" or High-Frequency Gravitational Waves [12, p. 743] and even suggest a "gaser" generator of HFGWs [12, p. 747], analogous to a laser for electromagnetic generation.

Leonid Petrovich Grishchuk and Mikhail Vasilievich Sazhin in early 1974 authored a paper on "Emission of gravitational waves by an electromagnetic cavity" [13], which involved HFGWs. In August of 1974 G. F. Chapline, J. Nuckolls, and L. L. Woods suggested the generation of HFGWs by nuclear explosions [14] and in 1978 Vladimir Borisovich Braginsky[2] and Valentin N. Rudenko wrote about "Gravitational waves and the detection of gravitational radiation" [15]. In that regard, a more recent paper by Rudenko (with N. Kolosnitsyn) in "Physica Scripta" suggests it is possible to couple a HFGW Generator and Detector (theoretically, a possible communication link) with a HFGW amplitude sensitivity of $h \sim 10^{-31}$ m/m at frequencies in excess of 10^{10} Hz. The Russians were most interested in HFGWs during the "Cold War" especially in the 1970's. Then in 1979 Steven W. Hawking and W. Israel presented an actual definition for HFGWs in a book [83, p. 98]. They suggested HFGWs have frequencies in excess of 100 kHz.

In Germany, Professor Heinz Dehnen was developing another HFGW generator, which made use of an array of crystal oscillators. Dehnen concluded that utilizing the relatively large crystal oscillators then available, the generated HFGWs would be too weak to be of value. Giorgio Fontana in Italy had been studying another possible HFGE laboratory generator the HFGW of a Laser that he termed a "Gazer." Different from the LFGW research funding, all of this pre-2000 HFGW research was accomplished without funding by major foundations or agencies [16, 17].

One of the first practical HFGW detectors was developed at Birmingham University, England by Professor Mike Cruise and his graduate student Richard Ingley. Professor Cruise published research during the 1990s on an electromagnetic detector for very-

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[2] See paper [87] in this issue.

Fig. 2. The Cruise-Ingley Birmingham University HFGW Detector. (Photo by Robert M L Baker, Jr., during visit in 2003)

Fig. 3. The Blair Parametric Transducer Gravitational Wave Detector Component. (Photo by D. G. Blair)

high-frequency gravitational waves in "Class. Quantum Gravity" in 2000. Professor Cruise has published over 100 research papers and a textbook on "*The Principles of Space Instrument Design*". He is a member of the European Space Agency and a member of international teams searching for gravitational waves using ground based and space based facilities such as LIGO and the proposed Laser Interferometer Space Antenna (LISA). An interaction between a gravitational wave and the polarization vector of an electromagnetic (EM) wave is the basis for the Cruise-Ingley Birmingham HFGW detector. The polarization vector of the EM wave rotates about the direction of its propagation. If a resonant condition can be established with the EM wave always experiencing the same phase as the gravitational wave, then the effect is cumulative and can be enhanced linearly by repeated circuits of a closed loop. The detector measures changes in the polarization, using a short filament or probe, of the EM microwave beam (indicating the presence of a HFGW) propagating within a waveguide loop about one meter in diameter. This is about the wavelength of 300 MHz HFGWs [18—23]. A pair of the Cruise-Ingley HFGW detector loops is shown in Fig. 2.

Another of the early HFGW detectors was also developed in 1990s on the other side of our planet, in Australia, by the gravitational wave pioneer Professor David G. Blair [24—25]. It is a Parametric Transducer device that is essentially gravitational-wave antenna and in many ways similar to the Weber Bar detector. A view of the double transducer component is exhibited in Fig. 3. It is expected to be sensitive to HFGWs having space-time maximum fractional deformations or strain of $A \sim 1 \times 10^{-20}/\sqrt{\text{Hz}}$ meters per meter.

There was, however, no real acceptance of gravitational waves in the scientific community until some observations were made from the Arecibo Radio-Astronomy telescope in Puerto Rico in the 1970s of binary pulsar 1913+16. They were made by Joseph H. Taylor and his graduate student, Russell H. Hulse, and led to the indirect verification of gravitational waves and their being awarded the 1993 Nobel Prize. Now GW research began to flourish. The Nobel Prize legitimized the existence of gravitational waves. This acceptance led Kip Thorne and others, especially Ronald W. P. Drever, both from Caltech, to promote the Laser Interferometer Gravitational Observatory or LIGO low-frequency gravitational-wave detector with the US National Science Foundation. LIGO was developed to detect the intense gravitational waves theoretically generated by the merger of a binary pair of black holes [11, 26—28].

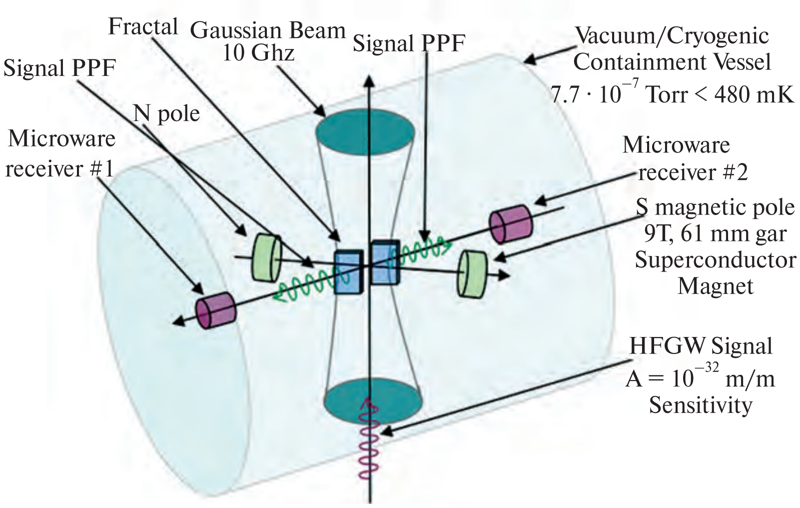

Fig. 4. Notional Drawing of Li-Baker HFGW Detector concept drawing by author

We remind that the High-Temperature Super-Conductor (HTSC) generator proposed by Giorgio Fontana from Italy is based upon the previously mentioned Halpern and Laurent studies and "...the properties of cooper-pair pairing states ..." [29, 30].

At this point in history let us pause and consider the state of Gravitational-Wave science at the turn of the Century, 2000. In the United States, as funded by the US National Science Foundation, the California Institute of Technology and other top institutions such as the Massachusetts Institute of Technology were actively pursuing the design and construction of the LFGW detector, LIGO. In England the first practical HFGW detector was under development by Professor Mike Cruise and his graduate student Richard Ingley. And in Australia Professor David G. Blair was actively involved in gravitational-wave research. I contacted the US National Security Agency (Hendge G., written communication from the United States National Security Agency to Robert M. L. Baker, Jr., dated on January 19, 2000). In Russia the top scientists had accomplished considerable HFGW research, especially concerning the "Gravitational-wave Hertz" experiment, the concept of the laboratory generation and detection of HFGWs. In Germany, Heinz Dehnen was analyzing a crystal-oscillator laboratory HFGW generator or transmitter. In Italy, Giorgio Fontana was analyzing a "HTSC Gazer," initially suggested by Halpern and Laurent, to generate HFGWs in the laboratory. Massimo Giovannini and others were continuing their research into the early universe generation of HFGWs. Fangyu Li had completed studies with Valentin Rudenko at the Sternberg Institute of Moscow State University.

In China Dr. Li had accomplished research into the Li-Effect in which HFGWs in a Gaussian electromagnetic field and an intense magnetic field could allow for the detection of HFGWs. This detector, termed the Li-Baker HFGW Detector, is under initial development in China at Chongqing University (see, Fig. 4).

For comparison of the Li-Effect with the (inverse) Gertsenshtein-Effect detectors, there is no laboratory-generated electromagnetic wave in the Gertsenshtein and, as previously mentioned, the Gertsenshtein Effect is extremely small and, as the JASON Report confirmed, has no value for HFGW detection. As of 2016, the Li-Baker detector is under development by Chongqing University in China, High-magnetic- field Center of Chinese Academy of Science (construction of high-strength, super conducting magnetic field element of figure 10-9(b)) and Southwest Jiaotong University in China. So far, the Li-Baker would be theoretically the most sensitive detector of weak HFGW's signal exhibiting an expected sensitivity of 10^{-32} meters per meter maximum amplitude strain in the mat of space-time (as determined by the analyses of Professor R. Clive Woods and others published in a 2011 edition of the "*Journal of Modern Physics*" [30]). With the super-

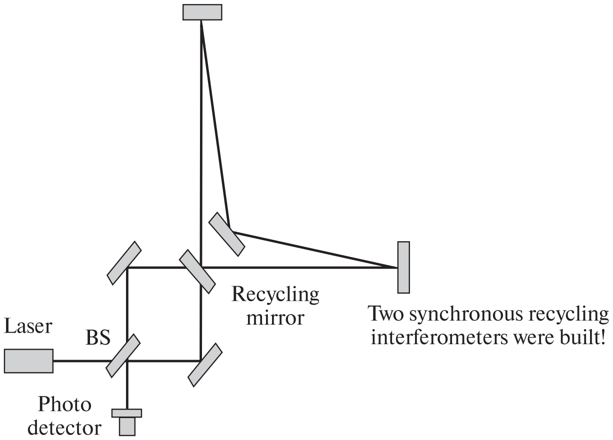

Fig. 5. Astronomical Observatory of Japan HFGW Detector

conductor magnetic field on, both noise and the signal perturbative photon flux (signal PPF) photons caused by the interaction of Gaussian-beam and coincident HFGWs (Li-effect) are detected at microwave detectors #1 and #2 (Fig. 4). With the magnetic field off only noise photons are detected. The difference between these detected photons then signals the presence of HFGWs. A basic problem is, as usual, noise – especially standard-quantum-limit noise inherent in the observation process itself caused by "quantum back action." Since, according to Heisenberg uncertainty, the photons involved in the observation themselves change what is being observed (slightly changing the geometry and/or time of arrival of signal PPF photons or slightly "moving" or "hitting against" what is being observed, so it is not where it was when it was observed) and are also noise sources.

The 100 MHz HFGW detector of the Astronomical Observatory of Japan, Fig. 5, had been built and reported on later in an article in the "Phys. Rev. D" [31]. It consists of two synchronous interferometers with arm lengths of 75 cm. Its maximum amplitude sensitivity was about $10^{-16}/\sqrt{\text{Hz}}$ meters per meter.

By the way, HFGWs cannot be detected by large-scale interferometer devices such as LIGO, Virgo or the proposed Laser Interferometer Space Antenna (LISA). According to one of the initial designers of LIGO, Peter Sven Shawhan, "at higher frequencies (above a kilohertz) the quantum nature of the laser beam (made up of discrete photons, albeit a large number of them) limits the precision of the measurements. Increased laser power would reduce the problem of quantum noise, but ultimately, the LIGO (and like) interferometers are not suited to measuring gravitational waves that stretch or shrink the arms much more rapidly than the time a photon typically remains in the optical cavity (laser arm), which is roughly a millisecond for these (long) interferometers (or approximately a one-kilocycle frequency limit) ..." [32]. LISA would be even less sensitivity to HFGWs, due to very much longer laser arms.

By 2000, research was picking up concerning detection of the LFGWs (funded by almost half a Billion dollars from the U S National Science Foundation), for LIGO for the detection of LFGWs most probably (theoretically) produced by the merger of black holes. To a far lesser, to an almost negligible degree, research on the HFGWs, most probably (also theoretically) produced by the early Universe or Big Bang, was continuing especially in China. As a portent of things to come, the very first patent specifically concerning HFGWs was filed in 1999, United States Patent Number 6,160,336, "Peak Power Energy Storage Device and Gravitational Wave Generator", including its continuation in part, "Gravitational Wave Generator," United States Patent Number 6,417,5971 B1 and "Gravitational Wave Generator Utilizing Submicroscopic Energizable Elements," United States Patent Number 6784591 B2. (Another related patent was Peoples Republic of China Patent Number 01814223.0, "Gravitational Wave Detector," filed July 13, 2001.) [3] Although HFGW research was encouraged by such important person as Buzz Aldrin, at the turn of the Century there had been no

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[3] After a rather long breather from my 1961 interest, a business associate of mine (not a scientist) Fred Noble and I filed that very first Patent Application for a GW generator in the world (now granted as United States Patent 6,160,336) on November 19, 1999. (Joseph Weber had a patent on an "Electromagnetic Coupled Detection of Dynamic Gravitational Force Gradients," United States Patent 3,722,288, filed in 1969, but it was unrelated to GWs). And then I was awarded United States Patent Number 6,417,597, for a "Gravitational Wave Generator," filed July 14, 2000. After achieving patent protection, I presented a paper entitled "Preliminary Tests of Fundamental Concepts Associated with Gravitational-Wave Spacecraft Propulsion," at the American Institute of Aeronautics and Astronautics: Space 2000 Conference and Exposition (Paper Number 2000-5250, September 20).

actual detection of gravitational waves of any frequency to inspire the scientific community.

Although there was no significant funding was available for HFGW research, Paul Murad was able to organize the first HFGW Conference or Workshop at The MITRE Corporation in McLean, Virginia, USA, May 6—9, 2003 [4]. The second HFGW International Workshop was organized by Eric Davis at the Institute of Advanced Studies at Austin (IASA), Texas, USA during September 17—20, 2007. Papers were presented by most of the attendees including Fangyu Li, Valentin Rudenko, Leonid Grishchuk, Gary Stephenson, Giorgio Fontana, and Clive Woods [33—37]. The Third International High-Frequency Gravitational Wave Workshop was held in Chengdu, China, April 7—9, 2017, and was attended by about 60 scientists, mostly from China.

After the 2nd HFGW Workshop on June 17, 2008, a research group called the JASONs, composed of very influential and respected university scientists, was given a briefing on the generation, detection and applications of high-frequency gravitational waves. The JASON Report (JSR-08-506) on that briefing was published in October, 2008. The Report was widely distributed to the US scientific community and various press organizations reported it. The JASON Report stated that "Our main conclusions are that the proposed applications of the science of HFGW are fundamentally wrong; that there can be no security threat; and that independent scientific and technical vetting of such hypothetical threats is generally necessary. We conclude that previous analysis of the Li-Baker detector concept is incorrect by many orders of magnitude..." The author of the JASON Report's basic premise for generating HFGWs was:

"A basic mechanism for generating a HFGW is the direct conversion of an electromagnetic wave into a gravitational one of the same frequency by a strong static magnetic field. This Gertsenshtein process is idealized in Fig. 3." In addition the Report states: "Proposed HFGW detectors have generally been based upon versions of the inverse Gertsenshtein process" (Italics added by the author for emphasis). These statements are both incorrect. As already mentioned, the Gertsenshtein process or effect was published in 1962 [9]. The effect is extremely weak and is not utilized in most of the modern HFGW generation, detection or applications.

In spite of the flawed JASON Report, others continued with HFGW research such as Gloria Garcia-Cuadrado in Spain and Professor R. Clive Woods now at the University of South Alabama and Christine S. Black who studied the HFGW radiation pattern [38—46]. Largely unaffected by the flawed JASON Report, research continued on relic HFGWs in Europe. The theme of the relic or Big-Bang generated HFGWs in the microwave band (~ 10^8—10^{11} Hz) was predicted by the quintessential inflationary models (QIM) of the early Universe by Massimo Giovannini [47—49], the Pre-Big Bang Scenario (PBBS) and some string cosmology scenarios [50—53]. These publications suggested HFGW random signals, and that the root-mean-square (rms) values of their dimensionless strain amplitudes might reach up to ~ 10^{-30}—$10^{-33}/\sqrt{\ }$ Hz. Because of their weakness and very high-frequency properties, such so-called "relic" GW waves are quite different from low-frequency GWs for which the laser GW detectors, such as LIGO, were expected to detect. Although the relic GWs have not been detected yet, according to Massimo Giovannini, we can be reasonably sure that the Earth is bathed in a sea of these relic HFGWs. Since 1978 such relic and primordial background HFGWs have been of ever increasing scientific interest as many researchers have shown [54—62]. In fact, the possible early Universe conception of giant black

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[4] In 2002 I traveled to Europe to present my HFGW ideas to John Miller (a famous astrophysicist, who worked with Steven Hawking) at the International School for Advanced Studies in Trieste, Italy; Mike Cruise, Dean of Science at Birmingham University, England (viewed his and Richard Ingley' s HFGW Detector); Professor Giorgio Fontana of the University of Trento, Italy (viewed the INFN HFGW Detector); Harald Dimmelmeier, the Max Planck Institute in Munich, Germany; and several scientists at INFN Genoa, Italy. At the last two meetings I delivered a lecture on HFGWs and recommended that an HFGW Working Group meeting be held early next year (2003) "...in order to trade ideas, stimulate thinking and define experimental parameters". After considerable work with Paul Murad, the Gravitational Wave Conference [International High-Frequency Wave (HFGW) Working Group] was organized for 2003 and Paul and I were co-chairs with Ning Li as a honorary co-chair. The Conference was dedicated to Robert Lull Forward who can be considered as the person who coined the term High-Frequency Gravitational Waves. The meeting attracted over 50 scientists from 14 countries and some 25 technical papers were presented.

holes by the direct collapse of primordial gas clouds, suggested recently by Sokol [69] could be studied by the analyses of relic HFGWs.

Based on high-dimensional (termed "bulk") space-time theories, it has also theoretically been shown by Massimo Giovannini and others, that all familiar matter fields are constrained to "live" on our three-dimensional, space-membrane or four-dimensional space-time membrane (for short "brane") world, while gravity is free to propagate in the extra dimensions, and the HFGWs (i.e., high-energy gravitons) would be more capable of carrying energy from our brane world than lower-frequency LFGWs. It is noted that propagation of the HFGWs may be a unique and effective way for exchanging energy and information between two adjacent parallel brane worlds or between "parallel universes". Moreover, if the pre-Big Bang scenario is correct, then the relic HFGWs would be an almost unique window from which one can look back into the early universe before the Big Bang. Although these theories and scenarios may be controversial and whether or not they include a fatal flaw remains to be determined. The successful detection of the HFGWs will certainly shed light on many of these theories. Also Einstein tells us that nothing in the Universe, light, gravitational waves, information in general, can exceed the speed of light. The ticking rate of the fast or slow clocks is here suggested to be related not only to time dilatation between moving frames of reference in Special Relativity, the strength of the gravitational field in General Relativity [63] where clocks in both cases move slowly, but also the speed of time may be related to the value of time itself. During a possible inflation of the early Universe (time is just getting started), clocks there might need to be very "fast" in order for the "material" of the early, rapidly inflating, Universe not to exceed the speed of light. Possibly clocks are still very slightly slowing down[5] after the Big Bang. There is considerable debate concerning the foregoing remarks. Since the early Universe may have been in relatively rapid motion, gravitational waves of high frequency may have been generated. Thus the detection of high-frequency gravitational waves could reveal the truth.

As already noted, Professor Fangyu Li has published more than sixty peer-reviewed papers concerning gravitational waves in internationally recognized scientific journals with coauthors such as Zhenyun Fang (see, for example, [64—67]). I will rely primarily on his presentations for the remainder of my remarks. Li considers HFGWs having frequencies above one MHz and lists the following effects that may generate HFGWs naturally: "For GW frequencies greater than 1 MHz: Cosmological signals from Planck era; K-K gravitons from brane oscillations in higher dimensions; interaction of astrophysical plasma with EM waves and Gamma bursts of magnetars. In order to understand the importance of HFGWs to cosmology it is important to understand the development of our Universe. It is also important to realize how quickly the early Universe developed, in about 10^{-42} to 10^{-34} seconds for the early "construction" phases and, as previously mentioned, that HFGWs emerged before regular electromagnetic waves such as light was radiated.

Einstein stated "The only reason for time is so that

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[5] (According to Julian Barbour [85]): "Clocks are useless if they do not march in step for otherwise we cannot keep appointments. Therefore it is not a clock that we must defne but clocks and the correlations between them as expressed in the marching-in-step criterion." But when they do not march in step that is where time as a "duration" becomes interesting. Again according Barbour "Occam's razor tells us to avoid redundant elements. All we need are differences. Indeed, the passage of time is always marked by difference, ..." Suppose you are a trainer of a runner who you just measured as doing a four-minute mile. Another trainer says that cannot be correct. "Your runner could not have improved that much, your stopwatch must be running slow since we all measured that he only ran a five-minute mile last year." Well, you argue "No, he has not improved at all, he ran at the same *intrinsic* speed as last year. You all had stopwatches that were running fast and miss-measured my runner's speed last year!" In this case last year's stop watches were moving 5 minutes/4 minutes = 1.25 minutes/minute times faster. Is there a way to establish that clocks (stopwatches) were moving with higher "speed" in the past? Essentially, an experiment may **not** be required. If there is a nuclear or molecular transient time (like Muon decay) that has been measured accurately by atomic clocks, then one should examine records and determine if a statistically significant reduction of the transient, e.g., Muon decay time (or, hypothetically, a runner's time to run a mile) over several years has occurred. If so, then their atomic clock "stop watches" must have been all running fast in the past and the speed of time was different and these clocks are still very slightly slowing down now after the Big Bang. Please see Section XVII of [86].

everything doesn't happen at once”. It should be added that the only reason for space is that everything doesn’t happen at one place – except, perhaps, at the beginning of a universe. There is a problem here. As Philip Ball [68] writes “... two particles *A* and *B* that have been prepared with ... ‘entangled’ properties ... for example if *A* has an upward pointing spin ... then *B* must be down and vice versa ... That means if one changes the spin on *A* it also (instantly) fixes the state of the entangled partner *B* – however far away that partner is”. Here’s a practical application: we want to have advance warning that the Klingons are attacking; so we entangle two electrons, keep one here at Space-command and have a Starship with the other several light years away. If the Klingons are spotted, then the Starship flips its electron’s spin. The other entangled electron also instantly flips and Space-command is immediately alerted to the Klingon attack! But according to Einstein’s special relativity, nothing (no information) can move faster than the speed of light, c. So maybe the effects of *A* and *B* are determined by some other event acting on them both — a “bridge” of time perhaps. HFGW research may help define that bridge. (Andrew Beckwith, “...quantum teleportation... Einstein-Rosenstein Brige...” [69]).

Other cosmological reserchers include the just quoted Professor Andrew Beckwith, internationally well-known cosmologist, Chongqing University [69—73], and Dr. Christian Corda’s works on the “magnetic” component of gravitational waves and on the stochastic background of relic gravitational waves [74—78].

On the low-frequency end of the gravitational wave spectrum, LFGWs, an interesting source would be the merger of binary black holes. This is the motivation for the LIGO’s development. In 1994, with a budget of USD 395 million, LIGO stood as the largest overall funded NSF project in history. The project broke ground at two locations: in Hanford, Washington, in late 1994 and in Livingston, Louisiana, in 1995. As construction neared completion in 1997, two organizational institutions were formed, LIGO Laboratory and LIGO Scientific Collaboration (LSC). The LIGO laboratory consists of the facilities supported by the NSF under LIGO Operation and Advanced R&D; this includes administration of the LIGO detector and test facilities. The LIGO Scientific Collaboration, composed of over one thousand scientists and engineers, is a forum for organizing technical and scientific research in LIGO. It is a separate organization from LIGO Laboratory with its own oversight. Initial LIGO operations between 2002 and 2010 did not detect any gravitational waves. In 2004 the funding and groundwork were laid for the next phase of LIGO development (called "Enhanced LIGO"). At this point the total funding for the LIGO Project reached in excess of onehalf a Billion dollars. This was followed by a multi-year shut-down while the detectors were replaced by much improved "Advanced LIGO" versions. By February 2015, after 21 years of R&D, the detectors were brought into engineering mode in both locations (Fig. 6).

Fig. 6. Four kilometer long Laser Interferometer Gravitational Observatory (LIGO) vacuum chamber

By mid-September 2015 "the world's largest gravitational-wave facility" completed a 5-year US$200-million overhaul at a total cost of $620 million. On September 18, 2015, Advanced LIGO began its first formal science observations at about four times the Advanced or Enhanced LIGO began its first formal science observations at about four times the sensitivity of the initial LIGO interferometers. Its sensitivity will be further enhanced until it reaches design sensitivity around 2021. On February 11, 2016, the LIGO Scientific Collaboration and Virgo Collaboration published

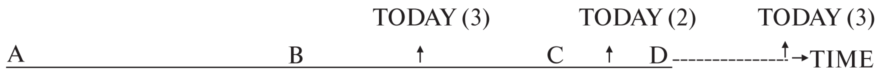

Fig. 7. Exoplanet advanced civilization time line or string, illustration by author

a paper about the detection of gravitational waves, from a signal detected at 09.51 UTC on 14 September 2015 of two ~30 solar mass black holes merging about 1.3 billion light-years from Earth [79].

Since the sensitivity of the present LIGOs is relatively small, they cannot now detect most double-neutron-star pulsars directly. On the other hand, in theory one can utilize a superconducting microwave cavity coupled to the acoustic motion of a superfluid helium-4 (fluid of an isotope of helium that flows freely without viscosity) in the presence of a LFGW having a maximum amplitude of roughly 10^{-24} m/m over a frequency range of 0.1 Hz to 1.500 Hz. (Singh, et al. [80]).

EXOPLANET APPLICATIONS OF HFGWS

Instead of conclusions on HFGW history, I would like to finish with several interesting perspectives concerning exoplanet applications of HFGWs. A comprehensive discussion can be found in my Book: "Gravitational Waves: the World of Tomorrow, a Primer, with Exercises, 3rd Printing, 2017. Our Galaxy (and there are 100 to 200 billion galaxies in our Universe) contains at least as many planets as stars and there are 200 to 500 billion stars per galaxy! Thus there may be as many as about 200,000,000,000 × ×500,000,000,000=100,000,000,000,000,000,000,000 (= 10^{23} or one followed by 23 zeroes or one hundred sextillion) Exoplanets out there! That does not mean that every star has a planet, but one may have 8 or 9 like our Sun, some may have none, some may have 12 or more, but on average assume one exoplanet per star. We should not rule out non-carbon based entities (e.g., Silicon based). In fact consciousness or intelligence might exist within stars or within any structure, even dark matter in the Universe; but for such "intelligence" to matter the ability to communicate is essential.

What might an Advanced Exoplanetary Being look like? Advanced Intelligent Civilizations May Include Communications with their Explorers. Homo sapiens and advanced civilizations may have a mean time to failure built into their evolutionary processes (Fermi's paradox). The Exoplanet Advances Civilization Time line with some explanation is given in Fig. 7. The Length of Time in Years between a Civilizations' Emergence of Cyborgs, gene engineered beings and/or some kind of Interstellar Communication Capability and their Demise, C to D or *d* (from Fig. 7) is presented in Table 1. There is also conjecture about the inevitability or improbability of the likelihood of intelligent life actually forming in our Universe. As Adrian Woolfson writes [81] "Gene editing ... allowing us to expunge unfavorable aspects of ourselves — such as our susceptibility to diseases and aging — while enabling the introduction of more appealing features ... humanlike organisms would be a near inevitability ...". Let us, however, assume the emergence of some exoplanets of long living electronic/biological or genetically engineered intelligent beings.

Thus up to C our civilization would have survived about 2000 to 4000 generations. Assuming our civilization is about to evolve rapidly into advanced gene engineered or biological/electronic beings i.e., cyborgs at C it is estimated (or "conjectured") the longevity of our and other civilizations near us in our Galaxy to average about 400,000 years C to D. Various other alternatives are exhibited in Table 1. However, the demise of the advanced civilization might occur almost any time during the time interval between B and D. That is, during that time interval between B and D advanced civilizations could "blink" on at B and then off, that is reach its D. There are numerous values that could be chosen for these dates. Let us speculate that civilizations reach its D in a serial fashion. Of course, there could be overlap and the time spans would be quite randomly distributed. In order, however, to get some approximate numerical results simply assume that when one advanced civilization reaches its D ("blinks off") another civilization reaches its C ("blinks on"). In the numerical example, the number of such intervals would be 3.6 billion years divided by 400,000 years or 9,000. By

Table 1. **The Length of Time in Years between a Civilizations' Emergence of Cyborgs, gene engineered beings and/or Interstellar Communication Capability and their Demise, C to D or *d* (from Fig. 7)**

Generation length, years	No. of Generations					
	1	4	40	400	4,000	40,000
25	25	100	1,000	10,000	100,000	1,000,000
100	100	400	4,000	40,000	400,000	4,000,000
1,000	1,000	4,000	40,000	400,000	4,000,000	40,000,000
10,000	10,000	40,000	400,000	4,000,000	40,000,000	4×10^8
100,000	100,000	400,000	4,000,000	40,000,000	400,000,000	4×10^9
1,000,000	1,000,000	4,000,000	40,000,000	400,000,000	4,000,000,000	4×10^{10}

Table 2. **Number, N, of potential intercommunicating advanced civilizations as a function of the years between C to D or *d***

d years between C to D	N
4,000	1.48
40,000	14,800
400,000	***1.48×10^8***
4,000,000	1.48×10^{12}
40,000,000	1.48×10^{16}

the way, only if TODAY were at TODAY (2) would a particular one of the 9,000 advanced civilizations have the opportunity for interstellar communication that could be intercepted by us. But only those Worlds that are clustered together close enough to communicate with each other in a time span less than 400,000 light years apart in the numerical example could communicate in time before their demise D. Let us suppose that the average distance apart of stars in our Galaxy is about five light years, so that minimum intercommunication time would average some 2 × 5 = 10 years for this pair of close-by stellar exoplanetary systems.

Potential Intercommunicating Civilizations. In general, if we define *d* as the time interval C to D in years as found, for example, in the entries of Table 1, then given a 5 light year average distance apart of the stars and their advanced exoplanet civilizations in our neighborhood of the Universe, they could be $S = (d/5)/2 = d/10$ stars away. In the numerical example $S = 400.000/10 = 40.000$. Thus the number, *n*, of such potentially intercommunicating civilizations in the spherical volume of interstellar communicating exoplanet civilizations would be $n = (4\pi/3)\, S^3$, which is somewhat similar to the factor $R^* \times f_p$ in the Drake equation.

Number N of potential interstellar-communicating Exoplanets. In the example, $n = 2.68 \times 10^{14}$. Of course, this number must be greatly reduced, which also will reduce the estimated number of the true potential intercommunicating advanced civilizations around Earth. Let us assume that on average only one out of ten exoplanets would be in the habitable zone between the freezing and boiling point of water (probably conservative because not all intelligent extraterrestrial life may need to be in this temperature range). Next, let us assume that only one out of ten of these habitable exoplanets will reach the advanced stage C. Finally, cut their number in half to account for very old and dead exoplanetary civilizations and then by dividing by the number of stars that have reached C but have not reached D or, in the numerical example, divided by 2 × 9000. So, under these arbitrarily parameters, the actual number *N* of potential interstellar-communicating Exoplanets is estimated to be $N = 2.68 \times 10^{14} / 10 \times 10 \times 9000 = 1.485 \times 10^8$.

Each intercommunicating advanced civilization may be comprised of thousands, if not millions, of independent interstellar transmitting/ receiving individuals or cyborg entities. There are about three million independent radio operators or "hams" worldwide on our planet. Thus we are considering a minimum of intercommunications (see, Table 2).

Fig. 8. Small Spherical Starcraft

Potential Frequency of Intercepts. In the numerical example for the 0.1*d* case there might be 550,000 possible messages to intercept each year or about 1500 per day. It is also interesting to note the distance of the stars/exoplanets in light years for 0.1*d* and 0.001*d*. These distances are, for the most part, in our Galaxy. Since HFGWs are not absorbed by interstellar material as are EM waves, an advanced civilization would choose HFGWs for interstellar and other communications purposes.

Can Interferometer GW Detectors like LISA detect the HFGW Exoplanet Intercommunications? The answer is still NO! Here again is the problem with higher frequencies: One has to "observe" the interference pattern between the LIGO legs caused by the passage of a gravitational wave. As Peter Sven Shawhan, a key member of the team that assembled and tested the original LIGO, stated, "At higher frequencies, the quantum nature of the laser beam (made of discrete photons, albeit a large number of them) limits the precision of the measurement. Increased laser power would reduce the problem of quantum noise, but ultimately the LIGO (and other) interferometers are not suited to measuring gravitational waves that stretch or shrink the arms much more rapidly than the time a photon typically remains in the optical cavity (the arms of the interferometers), which is roughly a millisecond for these (LIGO) interferometers." A millisecond is one thousandths of a second and equivalent to 1000 cycles per second or a kilohertz or 10^3 Hz. In a less technical fashion, the easiest explanation to understand the LIGO frequency limitation is to visualize old radio antennas and modern satellite-dish antennas. The former were utilized to detect rather long radio low-frequency waves and would often consist of a long antenna wire. The latter is utilized to detect very high-frequency microwaves and consist of relatively small satellite dishes. It would be impossible for a radio wire antenna to detect high-frequency microwaves, just as the LIGO "antenna" cannot detect high-frequency gravitational waves.

What are we going to do with the intercepted signal between Exoplanets? First, we must decode it. No doubt it will not be Morse Code. Probably not any kind of encryption that National Security Agency of the US can handle right away. As Richard Grey recently suggested: "...we may all one day speak telepathically so it may be brainwaves!" Second, what will we learn from the intercepted messages? Here is where mankind may have great benefit from learning what the messages are about and "tell" us how to improve our way of life. But, this intercept will also be a Cataclysmic Event and may even lead to religious and other turmoil on our little planet!

How shall we prepare? Conduct research in cryptography with special attention to the possible interception of "brain-wave" communications. Conduct research and development of high-frequency gravitational wave (HFGW) detectors or receivers.

Application of High-Frequency Gravitational Waves to Interstellar Travel. A HFGW alternative to the Starshot Project, suggested by Stephen Hawking to send a small Starship microchip to the nearest star, can be described briefly as follows. Instead of 100-gigawatt electromagnetic laser beams ("pushing" small microchip Starcraft) which are easily absorbed by interstellar material and Starcraft "solar sails" subject to ablation by such strong lasers, a few powerful HFGW beams, reflected by a possible Starcraft HFGW mirror, (hence a "pushing" force due to reflection) could be employed. The HFGW beams would not be intercepted by the Earth's rotation or orbital motion since the Earth is transparent to GWs. HFGW frequency would be quite high in order to reduce GW beam widening due to diffraction. Such a HFGW mirror could propel the little GW Starcraft.

Robert M L Baker, Jr. and Yaroslav S. Yatskiv at the MAO NAS of Ukraine. April 17, 2017, Kiev (Photo by P. Berczik)

Upon reflection of the HFGW beam, when modulated by the HFGW StarCraft's mirror, the HFGWs could also serve as a return communications link.

The GW Starcraft might have a spherical rather than a planer chip form. It might be more like a Ping-Pong ball as in Fig. 8. The Ping-Pong ball's equatorial cross section would be occupied by the Starcraft's High Temperature Super Conductor (HTSC) mirror and the rest of this volume occupied by small HTSC magnets, various nano-electronics and attitude control mechanisms. There could well be a flotilla of such GW Starcraft launched together. According to R. Clive Woods, the pressure on an ideal HFGW reflector (if experimentally demonstrated that GWs are slowed in a high-temperature semiconductor or HTSC) would be:

$$p\ (N/\mathrm{m}^2) = 2\ \sigma_E\ (\mathrm{J/m}^3),$$

where σ_E is the energy per unit volume contained in the HFGW. Specifically,

$$\sigma_E\ (\mathrm{J/m}^3) = S\ (\mathrm{W/m}^2)/\mathrm{c}\ (\mathrm{m/s}).$$

For the more technical reader, a good background for High-Frequency Gravitational Wave study can also be found in my Book: "Gravitational Waves: the World of Tomorrow, a Primer, with Exercises, 3rd Printing" [84].

GOAL

I believe that those interested in the research and development of High-Frequency Gravitational Waves should be guided by the LIGO approach for Low-Frequency Gravitational Waves. 625 million dollars and 21 years may not be necessary for HFGW Research and Development, but it is an interesting goal.

COMMENTARY FROM DEPUTY-EDITOR-IN-CHIEF

On behalf of the Editor Board of the "Space Science and Technology" journal I am grateful to Robert M L Baker, Jr., for his permission to publish this paper. It includes two lectures, which Robert Baker presented at the Main Astronomical Observatory of the National Academy of Sciences of Ukraine on April 17, 2017, when he and his wife, Mrs. Bonnie Sue Baker, have visited Kiev.

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Received 17.04.17

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ДОСЛІДЖЕННЯ ВИСОКОЧАСТОТНИХ ГРАВІТАЦІЙНИХ ХВИЛЬ ТА ЇХНЄ ВИКОРИСТАННЯ ДЛЯ ВИВЧЕННЯ ЕКЗОПЛАНЕТ

Вперше обговорюється історія досліджень високочастотних гравітаційних (ВЧГХ, HFGW). Упродовж багатьох років, починаючи з першої згадки Пуанкаре в 1905 р. про гравітаційні хвилі та пропозиції їхньої назви Робертом Л. Форвардом в 1961 р., відбувається жвава дискусія щодо міжнародних дослідницьких зусиль зареєструвати високочастотні гравітаційні хвилі. У статті висвітлені досягнення дослідників з Китаю, Росії, України, Англії, Австралії, Японії, Німеччини, Іспанії, Італії та США. Проводиться порівняння з дослідженнями низькочастотних гравітаційних хвиль (НЧГХ, LFGW), особливо за допомогою Лазерної інтерферометричної гравітаційної обсерваторії (ЛІГО, LIGO). Також подано декілька цікавих перспективних проектів використань високочастотних гравітаційних хвиль для завдань космології, проблем швидкості часу та, особливо, досліджень екзопланет.

Ключові слова: гравітаційні хвилі, високочастотні гравітаційні хвилі, HFGWs, детектори HFGW, швидкість часу, екзопланети, LIGO, Starshot.

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ИССЛЕДОВАНИЯ ВЫСОКОЧАСТОТНЫХ ГРАВИТАЦИОННЫХ ВОЛН И ИХ ИСПОЛЬЗОВАНИЕ ДЛЯ ИЗУЧЕНИЯ ЭКЗОПЛАНЕТ

Впервые обсуждается история исследований высокочастотных гравитационных волн (ВЧГВ, HFGW). На протяжении многих лет, начиная с первого упоминания Пуанкаре в 1905 г. о гравитационных волнах и предложения их названия Робертом Л. Форвардом в 1961 г., идет оживленная дискуссия относительно международных исследовательских усилий зарегистрировать высокочастотные гравитационные волны. В статье освещены достижения исследователей из Китая, России, Украины, Англии, Австралии, Японии, Германии, Испании, Италии и США. Проводится сравнение с исследованиями низкочастотных гравитационных волн (НЧГВ, LFGW), особенно с помощью Лазерной интерферометрической гравитационной обсерватории (ЛИГО, LIGO). Также представлены несколько перспективных проектов использования высокочастотных гравитационных волн для задач космологии, проблем скорости времени и, особенно, для исследований экзопланет.

Ключевые слова: гравитационные волны, высокочастотные гравитационные волны, HFGWs, детекторы HFGW, скорость времени, экзопланеты, LIGO, Starshot.