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Historical Article

New Astronomical Observations: Joseph Weber's Contribution to Gravitational Waves and Neutrinos Detection

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Abstract. Joseph Weber, form Maryland University, was a pioneer in the experimental research of gravitational waves and neutrinos. Today these two techniques are very promising for astronomical observation, since will allow to observe astrophysical phenomena under a new light. We review here almost 30 years of Weber's career spent on gravity waves and neutrinos; Weber's experimental results were strongly criticized by the international community, but his research, despite critics, boosted the brand new (in mid-sixties of last century) research field of gravity waves to become one of the most important in XXI century. On neutrino side, he found an unorthodox way to reduce the size of detectors typically huge and he claimed to observe neutrinos flux with a small pure crystal of sapphire.

Keywords. Gravitational wave, Neutrino, Joseph Weber, Bar detector, Torsion balance.

INTRODUCTION

The astronomic observations will grow rich, in the next few years, two new methods of investigation. Today the sky is observed and measured almost exclusively by electromagnetic radiation. Until 1950 the available radiation was only the visible or near-infrared. Then in the second half of the last century, thanks to enormous technological advances, we added X-ray radiation, microwaves, radio-waves that almost complete the electromagnetic spectrum. These frequencies allowed to discover objects like pulsars, quasars, neutron stars and cosmic background radiation. Many things are still hidden to electromagnetic radiation. An example is the photons (the quanta of electromagnetic field) that come from the sun. The earth is illuminated by a "old" radiation, about 100,000 years old. The photons are created in the center of the sun, but employ about 100,000 years to arrive on Earth surface. The reason is the very high temperature inside our star. Matter is not what we know at such temperature. The core of the sun has a density 150 times larger than water and a temperature of $1{,}5\text{x}10^7$ °C. The core is formed by a plasma of ions and electrons, which traps the light. Photons cannot escape from the core, except after a long time, this is because the plasma of ions and electrons is opaque to electromagnetic radiation (the scattering cross section of photons with plasma is much higher with respects to the ordinary matter, where nuclei and electrons form atoms). One type of particles, however, manages to escape quickly from the solar core and to get on the Earth after only 8 minutes, with a velocity very close to the speed of light. These particles are neutrinos. Hypothesized by Austrian physicist Wolfgang Pauli and structured theoretically by Enrico Fermi in the 1920s, neutrinos are elusive particles that do not interact electromagnetically, but only through the weak interaction. They are produced during the nuclear fusion process that occurs in the sun and tell us the types of nuclear reaction that is occurring inside our star. The typical decay that involves neutrino is the so called β-decay, where a free neutron *n* decays into a proton *p*, an electron e^- and an electronic antineutrino $\bar{\nu}_e$.[1]

$$n \rightarrow p + e^- + \overline{\nu_e}$$

Neutrinos can also reveal hidden features in supernovae explosions. The huge flow of neutrinos will invest the Earth when a supernova explodes. The neutrino detectors on the Earth will alert telescopes and radio telescopes on supernova position. In fact, the neutrinos emitted by the explosion will travel undisturbed towards us, while the electromagnetic radiation will need a bit of time, as it will encounter in its path the hot plasma of ions and electrons. There is a worldwide alert on neutrinos called SNEWS (supernova Early Warning System), active since 2005 with the participation of seven detectors around the world including the two Italian LVD and BOREXINO. Neutrino detection can give very precious information on neutron stars' structure and on the merger process between two neutron stars in a binary system.

The very new second method of astronomical investigation is the detection of gravitational waves. According to the present theories, such types of waves are emitted by nearly all astrophysical objects and the most violent ones give off gravity radiations in copious amounts. Supernova explosion observed via gravitational waves can reveal how the star collapse is going on, what happens to star core and how the final explosion takes place. The internal part of supernova will be accessible only to gravitational waves or neutrinos. Another violent astrophysical event is the black holes merging. Two black holes, orbiting one on each other (binary system), release gravitational waves when they become more and more close and at the end an enormous amount of gravity radiation will be emitted when they will merge into a more massive black hole. Black holes are the only massive astrophysical object that cannot be observed directly with electromagnetic waves detectors or neutrinos. Nothing can escape from black hole, neither light. But an exception are gravitational waves that can be observed during the merging of black holes binary systems.

Gravitational waves were predicted in 1916 by Einstein, by finding that they are the carrier of the energy of the gravitational field, as electromagnetic waves transport the energy of electromagnetic field. In 1915 Einstein developed, after seven years, the theory of general relativity[2] that fixed a lot of paradoxes present in the old Newtonian gravitational theory (see Ref. 3 for an introduction to general relativity). The gravity force in general relativity is due to the curvature of the spacetime that is generated by masses (as in Newtonian theory) but also by any form of energy and momentum. Einstein field equation in tensorial notation has a simple form of:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \qquad (1)$$

where *G* is the gravitational constant, c the speed of light in vacuum. A part from the constants, the equation tells that $G_{\mu\nu}$ called the Einstein tensor that contains the spacetime curvature, is equal to stress-energy tensor $T_{\mu\nu}$. In other words, the stress-energy tensor modifies the spacetime form flat ($T_{\mu\nu} = 0$) to curved ($T_{\mu\nu} \neq 0$). The indexes $\mu,\nu = 0,1,2,3$ (the spacetime has 4 dimensions, 3 space type, 1 time type and the index 0 is usually the time component), so the eq. 1 are in practice 16 equations. It is interesting to see how gravitational waves emerge from Einstein field equation (1), to estimate the order of magnitude of such space time ripples that can be detected on the Earth. The Einstein tensor depends in a complicated way by the spacetime metric $g_{\mu\nu}$ If the space is flat, called the Euclidian space, the spacetime metric is identified by the tensor $\eta_{\mu\nu}$ that is:

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (2)$$

We can suppose for the moment that extreme astrophysical events, like binary black holes merging, happen very distant form our observation point, and that we are in a place where the stress-energy tensor $T_{\mu\nu} = 0$ (no gravity at all). The flat space will become nearly flat when spacetime ripples, caused by some event, will hit our detector. In this weak field hypothesis, the metric tensor $g_{\mu\nu}$ becomes $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, where $h_{\mu\nu}$ is the correction to flat space and we can consider $|h_{\mu\nu}| << 1$. With the latter two hypothesis Einstein field equation eq. (1) becomes:

$$\frac{\partial^2 h_{\mu\nu}}{\partial^2 x_\mu} = -\frac{16\pi G}{c^4} T_{\mu\nu} = 0 \qquad (3)$$

Eq. (3) are now 4 equations since only the index v survived the index contraction. Eq (3) can be expressed in a more familiar way:

$$\left(-\frac{\partial^2}{\partial^2 t}+\nabla^2\right)h_{\mu\nu}=0 \tag{4}$$

that is the standard wave equation. The solution of Eq. (4) is:

$$A_{\mu\nu}\exp\left(i\omega t+ik_1x+ik_2y+ik_3z\right) \tag{5}$$

where k is the three-dimensional wave vector and ω is the frequency of the wave; so, the spacetime oscillates with an amplitude $A_{\mu\nu}$, after some distant astrophysical event. Eq. (5) is the gravitational wave. The first step to detect gravitational waves is to estimate their strength for a detector on Earth. The order of magnitude of the wave amplitude depends on the phenomena, for example one of the most violent one could be a supernova explosion and a formation of a black hole of 10 solar masses $\left(10M_{\odot}\right)$. Genearally the upper limit for $A\leq M/r$ where r is the distance from the event and M is the mass of the object; if it happens in Andromeda galaxy, that is the closest galaxy to our Milky Way, distant from Earth roughly 2,5 million of light-years, $A\leq 10^{-17}$. The probability to observe such close and violent event is very rare and the wave amplitude typical for events that can happen two-three times per year is 10^{-21}. So, the target for detector sensitivity should be 10^{-22}. The first who claimed to observe gravitational waves in 1969 was Joseph Weber.[4] He worked in his carrier on both gravitational waves and neutrino, mainly giving an enormous and unique boost to the first one.

RESULTS AND DISCUSSION

In the history of gravitational waves a prominent place belongs to Joseph Weber, American physicist of Maryland University. Early in his career he has proposed a mechanism that explained the proper operation of the laser,[5] but without funds to experimentally prove his idea, has been overtaken by others who have demonstrated the laser mechanism and got Nobel prizes and glory. Forced to change the research field, he went to Princeton University under the supervision of John Archibald Wheeler. Wheeler in the decades 1950-1970 was considered the main expert of general relativity.[6] Weber learned of the existence of gravitational waves and chose them as a research field. He was an experimental physicist, so he decided to design a detector for gravitational waves. After years of study to understand the best way to measure gravitational waves, he decided to use a bar detector, a resonant mass detector that responds to incident gravitational waves by vibrating.[7] The detector was a simple aluminum cylinder, 2 m long and with diameter of 96 cm. Gravitational waves, ripples of spacetime, would compress and then tend the bar. Weber chose the size of the bar to reveal the gravitational wave frequency of about 1600 Hz. He based the choice on very rough estimate. In the early 1960s a clear picture of which astronomical events could emit gravitational waves around 1 kHz was not clear. This frequency is typical of black holes and neutron stars binary systems that with a spiral motion merge and release a large part of their mass via gravitational waves. To measure the deformation of the bar detector, he adopted piezoelectric crystals, which property is that under mechanical deformation respond with an electric voltage, see Figure 1. In measuring this voltage, Weber could understand how his bar has been deformed from a gravitational wave. In the early sixties of last century, Weber was the only experimental physicist who developed a detector and tried to observe gravitational waves, while today there are four operating gravity waves observatories and other under construction or design. In the late sixties,[4,8] Weber began to publish data on the possible extent of gravitational waves. At that point, several research groups started gravitational waves search and adopted bar detectors to try to reveal the ripples of spacetime. No group in the early 1970s, however, was neither able to replicate Weber result's, nor confirm his results.[9] Weber continued to publish results of gravitational waves detection[10] and in the meanwhile he added a new bar detector placed about 1000 km away from the previous one. This method based on the coincidence

Figure 1. Weber's bar detector. Joseph Weber with his bar detector. The small metallic squares on the aluminum cylinder (the bar) are the piezoelectric crystals that were used to quantify the bar deformation. Image credit: University of Maryland Libraries Special Collections and University Archives.

between the two detectors, allowed to identify more easily spurious signals that come from any source but gravitational waves. Since Weber was the only one to detect gravitational, while all other experiments around the world failed, the physics community discredited Weber and his measurements were decreed not reproducible. For many physicists Weber made mistakes or manipulated data in identifying the threshold for gravity waves event detection. As a general rule an experiment must be repeated by anyone under the same conditions in different places and at different times, otherwise it is labeled not reproducible and it means that the original experiment is suffering from some weird error that alters the results.

We will not enter here into the dispute between Weber and the physics community, but a very interesting problem that plagues bar detectors is the uncertainty principle. Quantum mechanics, the theory in physics that very precisely describes the behavior of the infinitely small as atoms and elementary particles, includes the uncertainty principle. If we take an electron and, for instance, we want to measure at a given instant of time its position and its velocity very precisely, we would be disappointed. If we measure its position very precisely its speed will be almost completely indeterminate, and vice versa. So, nature does it on microscopic scales, but what does it happen in the macroscopic world to bar detectors that are two meters long? In 1978 the Russian physicist Braginsky showed that resonant bar detectors were affected by the uncertainty principle.[11] More accurately was the measurement of the position of one end of the bar, more unpredictable was the force that caused the vibration. By making calculations of the intensity of spacetime deformation due to the passage of gravitational waves, one get that powerful gravity waves were about 10 times weaker than the quantum limit of Braginsky for bar type detectors, meaning that the quantum fluctuations were much larger than gravitational wave signal; in other words, the wave amplitude limit of Weber's bar was 10^{-16}, accordingly to uncertainty principle. This could be the main reason for which none, except Weber, detected gravitational wave with bar detectors. The quantum limit will be always present any system, but different detectors have different quantum noise threshold.

Instead of bar detectors, one possible way to measure the deformation of space is to send light back and forth and measure how light travelling time changes. To do this, one can use a Michelson-type interferometer. The light from a laser crosses a beam splitter, which send half to one arm and half to the other interferometer arm (perpendicular to the first). The phase difference of photons in the two arms of the interferometer is correlated. When light comes back from the two arms an interference pattern is visible in the detector. This pattern will change if a gravitational wave will cross the interferometer and stretches and squeezes the spacetime. Interferometers have two main advantage with respect to bar detector, one is that they operate in range of frequency of about 1000 Hz and their sensitivity can reach very large value.

LIGO (Laser Interferometer Gravitational wave Observatory) is formed by 2 interferometers with 4 km long arms. Proposed in 1976 by Kip Thorne,[6] 40 years later in 2016 LIGO observed for the first time directly the ripples of spacetime.[12] To date there are two direct observations of gravitational waves by LIGO that occurred in 2016.[13] The first observation was caused by two black holes orbiting one around each other, with masses respectively 36 and 29 solar masses.[14] After the merge, a black hole of 62 solar masses has been created, while 3 solar masses instead have been converted into gravi-

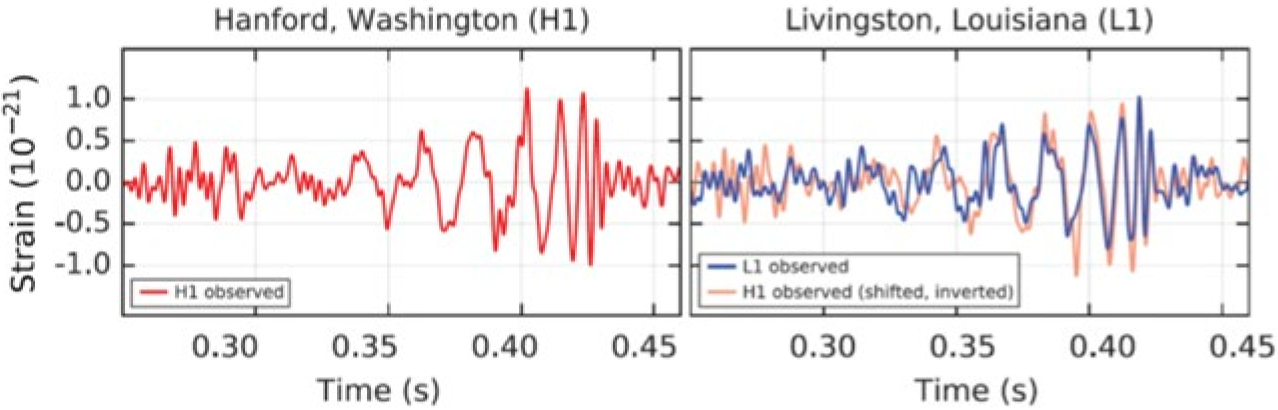

Figure 2. First gravity wave measured. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Image credit: LIGO, picture taken from Ref. 13.

tational waves that were measured by LIGO detectors. The event was distant from Earth 1,3 billion light-years and generated a wave amplitude (called also strain) of 2 10^{-21}. In Figure 2 the measurements from the two LIGO interferometers were depicted, around 0.4 s the two black holes were merged (courtesy of LIGO, Ref. 13).

There are other detectors similar to LIGO, the more similar is VIRGO, located in Italy, an interferometer of 3 km long arms (see Figure 3). VIRGO was upgraded during LIGO observation and will be in operation early in 2017. The Japanese observatory called KAGRA is under construction in Kamioka observatory, near the neutrino detector Super-Kamiokande, and it should be ready to run in 2018. The interferometric detectors work on frequency range from 10 Hz to 2000 Hz roughly. As for electromagnetic waves, gravitational waves exist in a very broad frequency window. Very challenging for European Space Agency is the project eLISA (Evolved Laser Interferometer Space Antenna), where 3 satellites (distant 1 million km one from each other) will form a giant Michelson interferometer. eLISA will work in a frequency range form few Hz to 10^{-5} Hz (complementary to observatories on Earth) allowing to observe gravitational signals from many astrophysical interesting sources such as binary stars within our galaxy and binary supermassive black holes in other galaxies. eLISA proposed launch date is 2034.

Joseph Weber's work inspired and boosted the research in gravitational waves detection. Kip Thorne, one of the founder of LIGO project, was inspired by Weber's research in mid-sixties of the last century and after a conference, where Weber showed his preliminary experimental work, he decided to investigated theoretically the gravitational waves.[6] Perhaps, without Weber pioneering work, we wouldn't have had any detection of gravity waves in 2016. He used very simple and cheap detector; nowadays we have very expensive observatories and the others planned will be more and more expensive, e.g. eLISA estimated cost is 2,4 billion of USD. On the other side, some research is still running on "alternative" detectors, based on resonant mass detectors. The bar type detector is replaced by spherical mass detector, that use the same working principle of the bar but with the advantage of having a larger frequency range. Two experiments are quite active, Mario Schenberg Brazialian graviton project[14] and MiniGRAIL of Leiden University in the Netherlands.[15] At the current time, no direct gravitational waves observation was reported from these two experiments, due to their quantum limit around $\approx 4\text{x}10^{-21}$, higher than LIGO measured signal in the first direct observation (see Figure 2).

Figure 3. EGO observatory. View of EGO (European Gravitational Observatory) that guest the experiment VIRGO. EGO is a French-Italian consortium and the observatory is located near Pisa (Italy). Image credit: VIRGO Collaboration.

The interest of Weber for gravitational waves weakened after the debate with physics community and his discredit on this research field. He continued to receive founding on gravitational wave detection, but he published most of his research on not peer review journals.[16] His interest moved towards another fundamental research line, the neutrino detection. In 1984 Weber proposed a new mechanism to detect neutrinos with a very simple apparatus.[17] Weber theoretical claim involved scattering of low energy neutrinos on an infinite stiff crystal. The weak interaction theory of Lee and Yang predicts a scattering cross section for low energy neutrinos by a quark, that depends on N, where N is the number of nuclei of the medium.[18] Weber coherent scattering theory applied to infinite stiff crystal predicts a scattering cross section that depended on N^2.[19] The major experiments around the world that detect neutrinos from various sources, as for instance ICE CUBE,[20] SUPERKAMIOKANDE,[21] BOREXINO,[22] have detectors formed by enormous amount of liquid-solid material (south pole ice, ultra-pure water, peculiar scintillator respectively). Neutrinos cross section is proportional to the number of molecules N of the detectors, for this reason to increase the probability of detection many experiments use very large amount of matter. The proposal of Weber for low energy neutrinos, applicable for example to radioactive source or to solar neutrinos could enhance instruments sensitivity by a factor of 10^{23} !

The theoretical work of Weber of 1985 was criticized by two papers of 1986 and 1987. The conclusion of both papers is,[23,24] as reported by Butler in Ref. 25: "Weber's derivation of large total cross section is wrong on the basis of elementary physical arguments and that is a result of an incorrect mathematical derivation". Weber in 1988 published a detailed paper where he showed experimentally how "coherent scattering of neutrinos can give measurable force due to coherent momentum transfer to crystal of cm of dimensions".[26] Weber used a torsion balance equipped with single crystal sapphire target. He had three different torsion balances for three different experiments. The low defect sapphire crystal used mimicked the infinite stiff crystal for low energy neutrinos predicted by Weber's theory.[19] In the first experiment, where neutrino energy was 12 keV, the balance was equipped with two identical mass bars. One made of lead, and the second made of titanium tritide, acting as antineutrino source, with an activity of roughly 3000 Ci). The β-decay from tritium created electrons and electronic antineutrinos. Such neutrinos flux is enough to move the balance of a measurable quantity. The measured force per antineutrino was $(1{,}05 \pm 0{,}12) \times 10^{-23}$ N cm^{-2} s^{-1}. In the second experiment Weber used the balance to measure the antineutrino flux from a nuclear reactor. In the third experiment Weber measured the solar antineutrino flux (neutrino energy from 0 keV to 430 keV). The scheme of the torsion balance used for solar antineutrinos is shown in Figure 4.

As reported by Weber in Ref. 25: "A diurnal effect is predicted as the position of the Sun changes, relative to the balance. We have been observing the diurnal effect during the past two years, with a peak, when the Sun is in the direction of the line normal to the line joining the two masses". In all three experiments the torsion balance of Weber succeeded to measure the antineutrino flux.

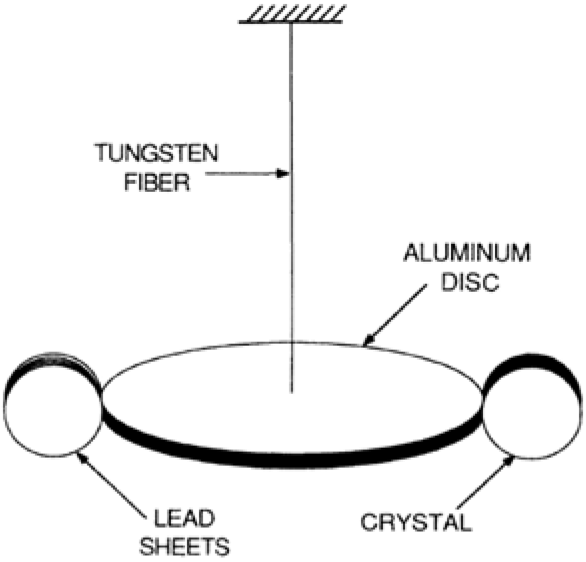

Figure 4. Solar antineutrino detector. Schematic view of torsion balance used by Weber in solar antineutrino experiment, where neutrino coherent scattering from sapphire crystal produced a measurable torque. Picture taken form Ref. 24. Image credit: American Physical Society.

Weber experimental paper, even though the theory of neutrino coherent scattering was considered wrong, were taken seriously by other research groups. The giant effect on solar antineutrinos observed by Weber inspired James Franson and Bryan Jacobs to replicate in a more precise and sophisticated way Weber's observations.[26] They used two torsion balances suspended in a vacuum chamber. The expected different angle between the two balances was measured trough a Mach-Zender interferometer. Weber in his paper in 1988 obtained a value of 0,86 for the efficiency of momentum transfer from antineutrinos to sapphire crystal. The very precise experiment of Franson and Jacobs gave an efficiency of 0,0033. In practice this value represented the lower limit of their apparatus; they measured nothing but apparatus noise. They concluded that their experiment was in strongly disagreement with Weber's one. After that, other three experiments with similar torsion balance were conducted by other teams. All of them concluded that Weber's observation of momentum transfer form solar antineutrinos to torsion balance was incorrect. No team measured any torque from neutrino scattering.[27-29] But in 2011 a team succeed to confirm Weber's experiment on solar antineutrinos.[30] They used a torsion balance under vacuum, with one target of low defect sapphire and the other made of lead. They observed the diurnal effect, with intensity similar to Weber's one. But except from the latter paper, where only preliminary results were reported, no detail study has been published yet. Weber unorthodox theory and experimental proof on neutrino scattering was considered not correct by scientific community, as happened for gravitational waves detection.

CONCLUSION

We reviewed here Joseph Weber's scientific career in gravitational waves and neutrinos detection. These two research fields are today considered the future of astrophysical observation. This demonstrated the intuition of Joseph Weber in working in fields of physics with great prospects. Weber was mainly a solitary researcher; in the majority of his papers he was the only contributing author. This fact was also confirmed by Kip Thorne in Ref. 6, where he reported the affinity between him and Weber in working in loneliness and in unexplored research fields. In the 1970s and 1980s the debate between Weber and scientific community was very harsh. The experimental results of Weber were almost considered not valid. This does not diminish the impulse that Weber's work has given and will give to both research fields. Today neutrino and gravity waves researches are what is called Big Science fields, in the sense of large projects involving large research groups for decades. The challenge is that neutrino and gravitational waves should become Small science, in the sense to have more compact and cheaper detectors. Weber with his experimental intuition performed experiments on both fields with a reasonable amount of money, but unfortunately, at the current time, the physics itself requires larger and expensive experiments to succeed.

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