Gravitational Waves Verify the Existence of Vacuum Energy

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Abstract: The biggest discrepancy in physics is the 10^{120} difference between the "critical" energy density of the universe from general relativity and the density of vacuum energy from quantum field theory. Analysis of the gravitational wave designated GW150914 shows that this wave encountered spacetime energy density of about 6.6 x 10^{31} J/m^3 at 250 Hz. Therefore, gravitational waves are encountering energy density consistent with the vacuum possessing zero point energy and far exceeding the critical energy density derived from general relativity. An analysis shows that the energy density encountered by gravitational waves scales with frequency squared (ω^2). This has application to quantum mechanics because the wave properties of particles also are waves in spacetime. An electron's Compton frequency would encounter vacuum energy density of about 10^{67} J/m^3. This is such a large number that a Planck length vacuum fluctuation in a volume with a Compton wavelength circumference can achieve an electron's energy. A model of vacuum energy is suggested which is based on spacetime being a sea of spacetime dipole waves. This model achieves the energy density predicted by quantum field theory and yet would be undetectable by fermion-based instruments.

1 Introduction

The first detection of a gravitational wave [1] designated GW150914 has been hailed as a very important advance in astronomy. It opens up a new way of observing massive objects in the universe and confirms another prediction of general relativity. All of this is true, but this paper makes the case that an unanticipated result of the observation of GW150914 is that it gives important new experimental support for the existence of vacuum energy. The connection is that gravitational waves propagate in the vacuum of spacetime and reveals hidden properties of spacetime. The properties of spacetime revealed will be shown to give insights the vacuum energy content of spacetime.

Quantum field theory can be interpreted as implying that the vacuum is not an empty void. Instead, the model of the vacuum obtained from quantum field theory possesses a large vacuum energy [2]. This has been interpreted as the zero point energy of the ground state of the standard model fields. The vacuum appears to be an empty void which has no activity on the macroscopic scale. However, the quantum vacuum has vacuum fluctuations on the scale of Planck length. On this small scale, the vacuum has been described as being a locally violent quantum foam [3, 4] Quantum field theory requires the vacuum to have a high energy density in order to achieve the incredible accuracy of QED and QCD calculations. Also energetic vacuum fluctuations are required for virtual particle formation/annihilation, the uncertainty principle, the Lamb shift and zero point energy in quantum systems.

There are also doubts about whether vacuum energy physically exists. There is no undisputed experimental evidence that vacuum energy exists. For example, the Casimir effect [5–7] is often cited as experimental proof of vacuum energy. There is definitely a force between two closely spaced metalized plates which has been measured and agrees with the QED predictions within a few percent. However, there are alternative explanations involving charges and currents [8] which generate the same magnitude of force between the plates.

The biggest reason that the majority of physicists believe that vacuum energy does not physically exist is that the implied energy density of vacuum energy is about 10^{112} J/m^3. For comparison, the "critical" energy density of the universe required to achieve flat spacetime is about 10^{-9} J/m^3. This is the famous 10^{120} discrepancy between general relativity (cosmology) and the theoretical predictions of quantum mechanics. This has been described as the largest discrepancy in all of physics and has been designated as the "vacuum catastrophe" [9, 10]. The critical energy density of the universe seems to be unquestionable. The value required to achieve flat spacetime derived by general relativity agrees to within 0.4% with observations made by the WMAP [11] and the Planck space mission [12]. The Planck space mission also determined that the energy content of the universe is about 4.9% baryonic matter, 26.8% dark matter and 68.3% dark energy. The dark energy appears to be a property of space itself and is sometimes referred to as the cosmological constant [13]. While vacuum energy is sometimes equated with dark energy or the cosmological constant, this paper is defining "vacuum energy" as the tremendously large energy density implied by quantum field theory.

Even though energy density of 10^{112} J/m^3 seems ridiculous, it cannot be easily rejected. Quantum mechanics is the most successful theory known to science. The concept of vacuum energy is an integral part of this successful theory. To cancel out this enormous energy density would take an equally enormous offsetting effect which is presently unknown. Also, the cancelation would need to eliminate 10^{112} J/m^3 while being careful not to eliminate the 10^{-9} J/m^3 that we can observe. Furthermore, the cancelation would need to leave all the effects of vacuum energy that are required by quantum mechanics.

Besides the lack of experimental evidence supporting vacuum energy, the other major problem is that energy density of 10^{112} J/m^3 would cause the entire universe to collapse into a black hole. All of these conflicting considerations seem impossible to satisfactorily resolve. However, this article will introduce new information hidden in gravitational waves which gives experimental evidence that vacuum energy actually exists. At the end of this article the question relating to gravitational collapse will be addresses.

2 Gravitational Wave Background Information

Gravitational waves (hereafter abbreviated GWs) were always considered to be a controversial prediction of general relativity. Their existence was debated at conferences and they were not detected even after 50 years of experimental attempts. Then in September 2015 the LIGO experiment started a new series of observations using instruments with increased sensitivity. Within two days of restarting, the two separate LIGO interferometers detected the GWs emitted by the merging of two black holes at a distance of 1.3 billion light years. A second, weaker GW designated GW151226 was also detected in December 2015 [14].

GWs propagate in the medium of spacetime. They are transverse quadrupole waves which slightly distort the "fabric of space". For example, a GW propagating in the "Z" direction would cause a sphere made out of baryonic matter such as aluminum to become an oscillating ellipsoid. When the sphere expands in the X direction it contracts in the Y direction and vice versa. The GW produces: 1) no change in the total volume of the oscillating sphere 2) no change in the rate of time, 3) no displacement of the center of mass of the oscillating sphere.

Point #3 addresses one common misconception about the effects of a GW. If there are two isolated masses such as two interferometer mirrors suspended by wires, the passage of a GW achieves a modulation of the distance between the center of mass of these two mirrors without displacing the center of mass of either mirror. The popular press usually describes the GW as physically displacing the mirrors, but this is wrong. The GW is a transverse wave that effects the transverse space dimensions in a way that the proper distance between points changes. The GW is not absorbed or reflected by ordinary matter. Therefore, there is no momentum transferred from the GW to the center of mass of an object. Using the previous coordinates, if a rod is oriented in the X polarization direction when a GW passes, the GW will affect space in a way that changes the proper distance between the atoms of the rod. The atoms perceive the change in distance and attempt to restore the correct separation distance. This causes the length of the rod to expand and contract as the GW passes. The ends of the rod will be accelerated as the rod oscillates but the center of mass of the rod will not be displaced. Similarly, the GW changes the properties of spacetime such that proper distance between the interferometer mirrors changes without actually displacing the center of mass of the mirrors. The change in the properties of spacetime also affects the wavelength/frequency of LIGO's laser beams. The mirrors do not move but the energy of the photons slightly change as the GW passes. The light in one arm is slightly redshifted to a lower frequency (longer wavelength) and the light in the other arm is slightly blue shifted to a higher frequency (shorter wavelength). This effect is then reversed multiple times as the wave passes. The difference in wavelength is detected by the interferometer as an interference shift.

There are similarities between a GW propagating in the medium of spacetime and a sound wave propagating in an acoustic medium. The same way that it is possible to obtain information about the physical properties of an acoustic medium by analyzing its acoustic properties, so also it is possible to gain insights into the physical properties of spacetime by analyzing gravitational wave data. However, to gain a deeper insight into the physical properties of spacetime, it is necessary to understand the physical implications of the GW amplitude being measured. In acoustics, the amplitude is designated as particle displacement δ with units of length. This is easy to understand as the maximum oscillating distance a particle moves from the neutral position. There is an analogous maximum displacement of spacetime produced by a GW, but this cannot be directly measured.

If an interferometer is detecting a GW, it obtains a detected length change that we will designate $\Delta\ell$. This measurement is made over the round trip length of the interferometer that will be designated L. If we assume that L is much smaller than the GW wavelength ($L << \lambda$), then the maximum strain (maximum slope of the sinusoidal GW) can be approximated as $\Delta\ell/L$. Knowing the maximum slope, it is possible to calculate the maximum displacement as $\Delta L = ƛ\Delta\ell/L$ where ΔL is the maximum displacement and lambda bar is $ƛ = \lambda/2\pi$. It is possible to state the strain amplitude (A_s) of a gravitational wave using the maximum displacement ΔL and reduced wavelength $ƛ$ because: $A_s = \Delta L/ƛ$. It is also possible to make a connection between the particle displacement δ of acoustic equations and the displacement amplitude $\Delta L = A_s ƛ$ of GWs. Using this connection, it is possible to combine acoustic equations and GW equations to gain insights into the properties of spacetime.

Many of the equations dealing with GWs are complex, but one of the most useful is very simple. Eq. (1) below assumes a GW that is both a plane wave and sufficiently weak to ignore nonlinearities. In texts on GWs [15] this equation is usually written with the strain amplitude designated with the symbol "h". However, to avoid confusion with Planck's constant, Eq. (1) uses the symbol A_s. Also we are standardizing on the use of angular frequency ω. The 2π difference compared to frequency also requires the appropriate adjustment in the numerical constant.

$$I = \left(\frac{1}{16\pi}\right) A_S^2 \omega^2 \left(\frac{c^3}{G}\right) \tag{1}$$

Eq. (1) should be compared to the general intensity equation for the intensity of waves of any kind. This equation is: $I = kA^2\omega^2Z$. Comparing this to Eq. 1, it is obvious that in Eq. (1) the numerical constant $k = 1/16\pi$, the amplitude term $A = A_s$, and the impedance term is c^3/G. Blair [15] was the first person to identify the impedance of spacetime as $Z_s = c^3/G$. This is a very important insight into the properties of spacetime and will be used frequently later.

Now that we are armed with Z_s and $I = kA^2\omega^2Z$, we can write another equation for the energy density (U) of a wave propagating in spacetime at the speed of light The following equation will be used later.

$$U = \frac{I}{c} = \frac{kA^2\omega^2Z_S}{c} \tag{2}$$

3 Gravitational Wave Observation Verifies Vacuum Energy

Prior to the detection of the GW designated GW150914, there was a question about whether GWs actually existed in the theoretically predicted form. However, now that that doubt has been removed, it is possible to use the experimental observation [1] of GW150914 to support the contention that spacetime contains a form of energy density that strongly interacts with GWs but is undetectable to fermion-based instruments. GW150914 had a maximum frequency of about 250 Hz. We will be standardizing on angular frequency ω and reduced wavelength $\lambda\!\!\!^{-} = c/\omega$. Therefore GW150914 had a maximum angular frequency of $\omega = 1570$ s^{-1} and a reduced wavelength of $\lambda\!\!\!^{-} = 1.9 \times 10^5$ m. The measured strain amplitude was $A_s = \Delta L/\lambda\!\!\!^{-} = 10^{-21}$, therefore the displacement amplitude of the GW was $\Delta L = \lambda\!\!\!^{-} A_s = 1.9 \times 10^{-16}$ m. Substituting $A_s = 10^{-21}$ and $\omega = 1570$ s^{-1} into Eq. (1), we obtain that the observed GW intensity was $I = 0.02$ w/m^2. If this intensity was a 250 Hz sound, it would be 103 dB which is a very loud sound with a relatively large particle displacement amplitude. Yet the strain in spacetime produced by this GW was only 10^{-21}. Detecting this small signal required the most sensitive instruments ever made.

The maximum GW power emitted by GW150914 is reported [1] to be 3.6×10^{49} w. This emitted power is easily checked because it is the power required to achieve intensity of 0.02 w/m^2 over the area of a sphere with radius of 1.3 billion light years. The mass/energy radiated into GWs was equivalent to 3 solar masses (5×10^{47} J) which is about 4.6 % of the total mass of the two black holes before merging. At a distance of 1 wavelength (1.2×10^6 m) from the merging black holes, the GW power of 3.6×10^{49} w achieves intensity of about $I \approx 2 \times 10^{36}$ w/m^2 (ignoring nonlinearities). The strain amplitude at the distance of 1 wavelength was $A_s = \Delta L/\lambda\!\!\!^{-} \approx .01$ which implies maximum transverse displacement of $\Delta L = 1.9$ km on a GW that had a reduced wavelength of 190 km. However, the point that is most important for this paper is that intensity of $I = 2 \times 10^{36}$ w/m^2 implies that at this close distance, the GW had energy density (U_{GW}) of about $U_{GW} = I/c = 6.6 \times 10^{27}$ J/m^3. If spacetime is imagined as being an empty void, how is it possible for spacetime to achieve energy density of 6.6 x 10^{27} J/m^3? One possible answer is that gravitons create this energy density. However, "graviton" is just a word that does not explain the underlying physics of how this large energy density is achieved. The answer that will be justified in the remainder of this paper is that spacetime possesses vacuum energy (zero point energy) in excess of this energy density. A GW is analogous to an acoustic wave that is propagating in the medium of spacetime (a sea of vacuum energy).

The first step in this proof is to treat a GW as an acoustic wave and calculate the density ρ of the acoustic medium that is propagating the GW. The acoustic equation that will be used is another variation of $I = kA^2\omega^2 Z$ shown below. In the following equation, ca is the acoustic speed of sound and δ the particle's displacement amplitude with units of length.

$$I = kA^2\omega^2 Z = k\delta^2\omega^2(\rho c_a) \qquad (3)$$

In Eq. (3) it is obvious that impedance Z corresponds to the specific impedance $z_o = \rho c_a$ with units of kg/m^{2}s. In acoustics $k = 1$. We solve for the equivalent density ρ encountered by GW150914 by substituting the observed properties into Eq. (3). Set: $I = 0.02$ w/m^2; $\omega = 1570$ s^{-1}; $\delta = \Delta L = 1.9 \times 10^{-16}$ m and $c_a = c$. Also, the density ρ will be converted to energy density U.

$$\rho = \frac{I}{\omega^2\, \delta^2 c_a} = 7.4 \times 10^{14} \text{ kg/m}^3 \qquad (4)$$

$$U = \rho c^2 = 6.6 \times 10^{31} \text{ J/m}^3 \qquad (5)$$

This quantifies the stiffness of spacetime encountered by GW150914. Intensity of 20 mw/m^2 is equivalent 103 db sound at 250 Hz. However, it only produces a displacement of spacetime of about 10^{-16} m. To duplicate this, an acoustic medium would have to have density of the about 7 x 10^{14} kg/m^3 (energy density of about 7 x 10^{31} J/m^3) with a propagation speed equal to the speed of light. This density is about 10^{40} times greater density than the critical density of the universe from general relativity. This is such a large energy density that it would form a black hole with Schwarzschild radius of about 500 km. Since the universe has not collapsed into a black hole, how do we reconcile the energy density of the universe encountered by GWs and the critical energy density of the universe from general relativity? To answer this question, it is first necessary to extract more insights into the properties of spacetime as revealed by GWs and the comparison to acoustic waves.

4 Interactive Impedance of Spacetime

A GW is a transverse wave that distorts a sphere as previously described. This has similarities to a sheer wave in acoustics, but there are also differences. We will first analyze the similarities in the impedance encountered by both types of waves. In both sound waves and GWs, it is possible to express amplitude either as a displacement amplitude ΔL with units of length or as a strain amplitude which is a dimensionless ratio $\Delta L/\lambda\!\!\!{}^{-}$. The important difference is that the strain amplitude contains $\lambda\!\!\!{}^{-}$, the reduced wavelength. Therefore, strain amplitude is wavelength/frequency dependent. This point is made because next we will compare the impedance encountered by GWs to the impedance encountered by acoustic waves. To make this comparison, it is necessary to convert the impedance of spacetime $Z_s = c^3/G$ with units of kg/s to the impedance format compatible with displacement amplitude which requires units of kg/m^{2}s. To accomplish this we need to transfer the $1/\lambda\!\!\!{}^{-2}$ term present in A_s^2 to a new definition of spacetime impedance (designated Z_i) that is compatible with displacement amplitude with units of length. The interactive impedance Z_i shown in Eq. (7) is frequency dependent.

$$A_S^2 Z_S = \left(\frac{\Delta L}{\lambda\!\!\!{}^{-}}\right)^2 Z_S = \Delta L^2\left(\frac{Z_S}{\lambda\!\!\!{}^{-2}}\right) \tag{6}$$

$$Z_i \equiv \frac{Z_S}{\lambda\!\!\!{}^{-2}} = \frac{c\omega^2}{G} \tag{7}$$

Z_i has the same units and the same physical property as the specific acoustic impedance $z_o = \rho c_a$. It is now possible to make a comparison between these two types of impedances at a specified frequency. For example, a GW with frequency of 1,000 Hz ($\lambda\!\!\!{}^{-} = 4.78 \times 10^4$ m) encounters spacetime as having an interactive impedance of $z_i = Z_s/\lambda\!\!\!{}^{-2} \approx 1.8 \times 10^{26}$ kg/m^{2}s. We will compare this to the acoustic impedance of osmium which has impedance of $z_o = 1.1 \times 10^8$ kg/m^{2}s. This is the highest acoustic impedance of any solid. Therefore at 1,000 Hz, the impedance of spacetime is a factor of about 10^{18} greater than the impedance of osmium.

Suppose we extend this comparison to the densest macroscopic material anywhere in the universe. Epstein [17] has analyzed the density, temperature and speed of sound in a neutron star. The central core of a neutron star has the highest density and a recently formed neutron star has the highest speed of sound because it has the highest temperature. For this analysis we will choose a plausible core density of $\rho = 3 \times 10^{17}$ kg/m^3 and temperature of 2.5×10^{11} °K. This temperature corresponds to a speed of sound of about $c_a \approx 6 \times 10^7$ m/s which is about 20% of the speed of light. Therefore this hypothetical neutron star would have a specific acoustic impedance of about $z_o \approx 1.8 \times 10^{25}$ kg/m^{2}s. This is still a factor of about 10 less than the impedance of spacetime experienced by a GW at 1,000 Hz ($z_i \approx 1.8 \times 10^{26}$ kg/m^{2}s). Furthermore, since the interactive impedance of spacetime scales with ω^2, this difference increases at higher frequencies. If there was a hypothetical GW at Planck frequency $\omega_p = 1.8 \times 10^{43}\ s^{-1}$, this GW would encounter interactive impedance of spacetime is $z_i \approx 10^{105}$ kg/m^{2}s. Therefore, at this limiting frequency the interactive impedance of spacetime is more than 10^{80} times larger than the impedance at the core of a neutron star where the speed of sound approaches the speed of light.

Pause and think about these statements for a moment. At 1,000 Hz, GWs perceive spacetime to have impedance roughly a billion, billion times greater than the impedance of osmium or 10 times greater than the impedance of the core of a neutron star. Clearly, this implies that a GW is interacting with a tremendously large energy density which is undetectable to our fermionic-based instruments. What is causing the "fabric of spacetime" to act like an extremely stiff elastic medium for GW propagation? To answer this question, we will start with some thought experiments.

Suppose that we have a chamber filled with an ideal gas. This gas has a density ρ, and acoustic speed of sound c_a. The specific impedance of this gas is $z_o = \rho c_a$. Now suppose that we introduced ultrasonic sound waves propagating in several directions into this gas. The volume is fixed so the density remains the same. Also the ideal gas is perfectly elastic so the ultrasound would theoretically require the addition of an absorber to eliminate the sound waves. When the ultrasonic sound waves are present, they introduce additional organized energy to the gas particles and increase their average speed of the particles. This increases the energy density, the speed of sound and the impedance of the gas. If a lower frequency sound is introduced to the gas, the lower frequency sound would encounter a different impedance depending on whether the ultrasonic sound was present or absent. The lower frequency sound would compressing and expanding volumes of the ideal gas. This would introduce slight frequency shifts to the ultrasound resulting in energy exchange. This ultimately produces a change in the impedance experienced by the low frequency sound.

Now suppose that spacetime contains the spacetime waves which are at a very high frequency and produce a very small displacement of spacetime. Such waves might be undetectable to fermion-based instruments, but GWs would compresses and expand these waves which slightly increases and decreases their frequency. This would introduce redshifts and blue shifts in these high frequency waves similar to the red/blue shifts which GW150914 produced in the LIGO laser beams. If the energy density of the high frequency waves was very large, then the high frequency waves would make spacetime respond like a stiff, elastic material which exhibits a large impedance. Also the coupling constant and therefore the stiffness encountered by a GW would increase with frequency.

5 Interactive Energy Density of Spacetime

Quantum field theory has been telling us that there is a large energy density in the vacuum. This energy has been characterized as vacuum fluctuations associated with the uncertainty principle. However, to understand this vacuum energy it is necessary to quantify and characterize vacuum energy. It is possible to examine GW equations to extract the equivalent density ρ and the energy density U that the GWs encounter as they propagate through the medium of spacetime. Eq. (7) has already defined the interactive impedance of spacetime $Z_i = c\omega^2/G$. This impedance is analogous to the specific acoustic impedance $z_o = \rho c_a$. Both Z_i and z_o have the same units and represent the same concept. Therefore, we can determine the "interactive density of spacetime ρ_i" encountered by the GW from $Z_i = \rho_i c$. The following symbols are used: Planck angular frequency $\omega_p = \sqrt{c^5/\hbar G} \approx 1.85 \text{ x } 10^{43}$; Planck energy density $U_p = c^7/\hbar G^2 \approx 4.64 \text{ x } 10^{113}$ J/m^3, Planck density $\rho_p = c^5/\hbar G^2$ and the interactive energy density of spacetime $U_i = \rho_i c^2$.

$$Z_i = \rho_i c = \frac{c\omega^2}{G} \tag{8}$$

$$\rho_i = k\frac{\omega^2}{G} = k\left(\frac{\omega}{\omega_p}\right)^2 \rho_p \tag{9}$$

$$U_i = \rho_i c^2 = k\frac{\omega^2 c^2}{G} = k\left(\frac{\omega}{\omega_p}\right)^2 U_p \tag{10}$$

It is possible to check this because U_i and ρ_i can also be calculated from the energy density equation $U = kA^2\omega^2 Z_s/c$ which is Eq. (2). We will be solving for the interactive energy density of spacetime when a spacetime wave achieves the maximum possible strain amplitude which occurs when $A_s = 1$. The reasoning is that the definition of the interactive energy density is the total energy density accessible at frequency ω. The strain amplitude is defined as $A_s \equiv \Delta L/\lambdabar$, so the maximum possible value of ΔL at a given frequency is $\Delta L = \lambdabar$. This is 100% distortion of spacetime for that frequency. In Eq. (11) below, we will set $A_s = \lambdabar/\lambdabar = 1$ and $Z = c^3/G$ into Eq. (2) and yield an answer that is the same as Eq. (10).

$$U = \frac{kA^2\omega^2 Z}{c} = \frac{k1^2\omega^2}{c}\left(\frac{c^3}{G}\right) = \frac{k\omega^2 c^2}{G} = U_i \tag{11}$$

Eq. (9 - 11) are important because they quantify key properties of vacuum energy. Perhaps most revealing is the portion of Eq. (11) which is $U_i = k(\omega/\omega_p)^2 U_p$. Planck energy density ($U_p = c^7/\hbar G^2 \approx 5 \text{ x } 10^{113}$ J/m^3) can be visualized as zero point energy where Planck frequency waves in spacetime possess Planck energy in Planck volume (L_p^3). The numerical constant k is less than 1 so this zero point energy is less than Planck energy density by the numerical factor k. If another wave in spacetime is introduced into this sea of waves Planck waves, there would be an interaction between these two types of wave. The degree of coupling between these two types of waves would have a frequency mismatch if the introduced wave was less than Planck frequency. A coupling constant of $(\omega/\omega_p)^2$ is reasonable. For GWs, the numerical constant k is $k = 1/16\pi$ as stated for Eq. (1).

Vacuum energy is by far the largest component of the universe. Baryonic matter, dark matter and dark energy are trivial components of the universe compared to the vastly larger energy content of vacuum energy. Failure to recognize the physical presence of vacuum energy removes a key element required to explain the cause of many of the laws of physics. An analogy would be a fish that lives at the bottom of the ocean but the fish fails to recognize the existence of water. This hypothetical fish would be able to designate laws of physics applicable to its world, but the underlying cause of these laws would be a mystery. For example, a bubble would be a mysterious particle to this hypothetical fish. Similarly, an electron appears to us to be a mysterious point particle that somehow possess energy of 511,000 eV, angular momentum of $\hbar/2$, wave properties and probabilistic characteristics. To make progress in analyzing and conceptually understanding these properties, it is necessary to realize that the electron is immersed in a sea of vacuum fluctuations with a large energy density.

6 Spacetime Dipole Waves

In physics there are several examples of hard to detect entities. For example, about 70 billion solar neutrinos per second [18, 19] are passing unnoticed through every square centimeter of the earth perpendicular to the sun. Dark matter is widely accepted because of its gravitational effects, but it is so elusive that it has never been detected in a laboratory experiment. Dark energy is even more mysterious. Its effects on the expansion of the universe only became obvious by observing distant galaxies. If we could only make observations and experiments within the Milky Way Galaxy, then dark energy would be completely unobservable. The point is that there are other examples besides vacuum energy of difficult to detect entities that are accepted in physics. Therefore, it should not be surprising that vacuum energy can physically exist and yet not interact with baryonic matter on the macroscopic scale. Vacuum energy has been theoretically predicted by quantum field theory. Now the existence of vacuum energy has been detected on the macroscopic scale by its interaction with GWs.

Next we will switch to suggest a proposed model of vacuum energy. The model must explain how vacuum energy fits the previously enumerated characteristics including: being unobservable to fermion-based instruments, having the frequency dependent energy density of Eq. (10), strongly interacting with GWs and not creating a gravitational collapse. A model of energetic spacetime and fundamental particles compatible with this model has previously been presented [20] but that paper was written before GW150914 was detected. A brief summary of some parts of this model of vacuum energy will be given here. However, it is not necessary to accept this proposed model of vacuum energy in order to accept the physical existence of vacuum energy.

So far in this paper, the only type of wave in spacetime mentioned has been quadrupole GWs. On the macroscopic scale covered by general relativity, quadrupole (or higher order) GWs are the only type of spacetime waves permitted by the conservation of momentum. GWs distort a sphere so that it becomes an oscillating ellipsoid with no change in either volume or the rate of time. However, the most fundamental type of wave in spacetime would be a "spacetime dipole wave" which would modulate both space (volume) and modulate the rate of time. The spacial modulation would cause proper volume to expand and contract such that the distance between two stationary points would change.

However, spacetime dipole waves have an important limitation. They cannot produce a spatial displacement that exceeds ±Planck length (L_p) or a temporal displacement (difference between perfect clocks) that exceeds ±Planck time (T_p). If they exceeded this limit, it can be shown that macroscopic spacetime dipole waves would violate the conservation of momentum. Also spacetime dipole waves cannot be generated by accelerating matter. Therefore, spacetime dipole waves are only mentioned briefly in standard texts on general relativity [21] to make the point that they are impossible on the macroscopic scale addressed by general relativity. However, they are allowed by the uncertainty principle provided that the displacement amplitude is limited to Planck length/time. Support for their existence comes from the fact that that it is impossible (device independent) to make distance measurements more accurate than Planck length and time measurements more accurate than Planck time [22-26]. This is the background "noise" of the quantum vacuum. It is no coincidence that the uncertainty principle allows Planck length/time displacements. It is proposed that these vacuum fluctuations ultimately *cause* the uncertainty principle. This universal sea of vacuum fluctuations will be called the "**spacetime field**".

Think about the implications of the vacuum being a sea of spacetime dipole waves. This would introduce an element of probability into any small scale measurement or prediction. There would be no such thing as classical determinism on the scale which would be affected by spacetime dipole waves. The laws of physics could only be stated as probabilities. However, this is exactly what we find. The probability of quantum mechanics takes over when the uncertainty introduced by the spacetime dipole waves becomes a factor.

This model of the spacetime field achieves the properties of zero point energy, vacuum fluctuations and vacuum energy. The proposed model is that spacetime dipole waves forms the equivalent of Planck frequency harmonic oscillators of zero point energy. This basic unit of zero point energy would have energy of $E = ½\hbar\omega_p = ½E_p = ½\sqrt{\hbar c^5/G}$ (half Planck energy). The volume is not precisely known, but there are several reasons to believe that is the volume of a sphere that has a radius of Planck length. This volume is: $V_{zp} = (4\pi L_p^3/3)$. Lower frequencies and larger volumes can be made of combinations of this higher frequency building block. The lower frequencies would have lower energy and lower energy density but the analysis is beyond the scope of this paper. The energy density of Planck frequency harmonic oscillators can be obtained from $U_V = E_p/2V_{zp}$.

$$U_V = \frac{E_p}{2V_{zp}} = \frac{1}{2}\sqrt{\frac{\hbar c^5}{G}}\left(\frac{3}{4\pi L_p^3}\right) = \left(\frac{3}{8\pi}\right)\left(\frac{c^7}{\hbar G^2}\right) = \left(\frac{3}{8\pi}\right)U_p = 5.5 \text{ x } 10^{112}\ \text{J/m}^3 \tag{12}$$

The same answer can be obtained if we made the appropriate substitutions into Eq. (2).

7 Critical Density of the Universe

So far these calculations have yielded very large energy densities. However, if we are claiming to be tapping into the underlying structure of spacetime, it should also be possible to calculate the critical energy density of the universe $U_c \approx 10^{-9}$ J/m^3 and the critical density of the universe $\rho_c \approx 10^{-26}$ kg/m^3. To do this, it is necessary to view the expansion of the universe as a portion of a wave with angular frequency equal to the inverse age of the universe $\omega_u = 1/t_u$ where t_u is the age of the universe in seconds. The actual age of the universe is about 13.8 billion years old, but this number incorporates nonlinear expansion rates over the age of the universe. To make a connection to the current critical density of the universe we need to use the age of the universe implied by the current expansion rate given by the Hubble constant $\mathcal{H}_o$. The Planck space mission [12] determined the value $\mathcal{H}_o = 67.8$ km/s/Mpc which converts to $2.2 \text{ x } 10^{-18}$ s^{-1} in SI units. Using this value of $\mathcal{H}_o$, the implied age of the universe is $t_u = 1/\mathcal{H}_o \approx 4.5 \text{ x } 10^{17}$ s = 14.4 billion years. Therefore the calculation will use $\omega = \omega_u = \mathcal{H}_o$. We can also say $\omega_u = c/ƛ_u$ where $ƛ_u$ is the reduced wavelength of the expanding universe. Since this expansion started from virtually zero, then $\Delta L = ƛ_u$ and $A_s = \Delta L/ƛ_u = ƛ_u/ƛ_u = 1$. Making these substitutions into Eq. (2) we have:

$$U = \frac{kA^2\omega^2 Z_s}{c} = \left(\frac{3}{8\pi}\right)1^2\mathcal{H}_o^2\left(\frac{c^3}{G}\right)\frac{1}{c} = \frac{3c^2\mathcal{H}_o^2}{8\pi G} = U_c \approx 10^{-9}\ \text{J/m}^3 \tag{13}$$

$$\rho_c = \frac{U_c}{c^2} = \frac{3\mathcal{H}_o^2}{8\pi G} \tag{14}$$

Eq. (14) corresponds to the equation for the critical density of the universe obtained from the Friedmann equations of general relativity [27]. The critical density of the universe assumes flat spacetime which has been experimentally confirmed by WMAP and the Planck mission. Also, if you compare Eq. (13) and Eq. (14), the only difference is that Eq. (13) uses $\omega = \omega_p$ and Eq. (14) uses $\omega = \mathcal{H}_o$. Both of these terms have units of s^{-1} and are squared in their respective equations. Therefore, the relationship between vacuum energy density U_V and the critical energy density of the universe U_c is:

$$\frac{U_V}{U_c} = \frac{\omega_p^2}{\mathcal{H}_o^2} = 7.5 \text{ x } 10^{121} \approx 10^{120} \tag{15}$$

8 Particles and Photons

So far, we have discussed frequencies appropriate for GWs and Planck frequency. However, suppose we switch from these frequency extremes to the Compton frequency of fundamental particles. Particles have wave properties which also affect the surrounding spacetime. A moving particle such as an electron exhibits de Broglie waves with wavelength $\lambda_d = h/mv$ and phase velocity $w_d = c^2/v$. The reason for mentioning this is that the underlying frequency generating the de Broglie waves in a moving frame of reference is $w_d/\lambda_d = mc^2/h = \omega_c/2\pi$ where ω_c is the fundamental particle's Compton angular frequency. An electron's Compton angular frequency is $\omega_c = mc^2/\hbar = 7.8 \text{ x } 10^{20}\ s^{-1}$. What vacuum energy density does this frequency encounter? Inserting $\omega = \omega_c$ into Eq. (10) gives: $U_i = k\omega^2c^2/G \approx 10^{67}$ J/m^3. In words, an electron's wave properties encounter the spacetime field as having energy density of about 10^{67} J/m^3. This is such a large number that a spacetime dipole wave with frequency ω_c can achieve an electron's energy in a spherical volume that is one Compton wavelength in circumference [20]. Therefore, vacuum fluctuations which displace spacetime by Planck length can momentarily appear to have an electron's energy and appear to be virtual electrons.

The standard model is a field theory which assumes that multiple fields fill the vacuum of spacetime. Fundamental particles are considered to be "excitations" of their respective fields [28]. It is proposed that there is only one field – the spacetime field. However, this field has multiple resonances which fulfill the function of the multiple fields of the standard model. The "excitation" which causes a portion of a standard model "field" to become a real particle is proposed to be a ½ ħ unit of quantized angular momentum.

In an article titled, "Energetic Spacetime: the New Aether" [29], the case is also made that electromagnetic radiation propagates in the medium of the spacetime field, just like GWs. This leads to the prediction [30] that GWs should cause spacetime to become a birefringent medium. The presence of GWs should cause properly oriented polarized light to slightly change its polarization. If this is correct, it would be possible to detect GWs by monitoring polarization rather than using interferometers. This would simplify the equipment, reduce the noise and give more information about the location of the source.

9 Gravitational Collapse Avoided

General relativity has as a premise that: *all energy creates gravity* [31]. This is such a key foundation of general relativity that the theoretical evidence from quantum field theory supporting the existence of vacuum energy has been generally discounted by most physicists. Since the universe has not collapsed into a black hole, a common assumption is that there must be some large unknown effect which cancels out vacuum energy. Now the observation of GWs forces us to reexamine whether ***all*** *energy creates gravity*. For example, the interactive density encountered by GW150914 ($\rho_i = 7.4 \times 10^{14}$ kg/m^3) is about 10^{40} times larger than the critical density ρ_c and should make the universe a black hole. Therefore, is it possible that vacuum energy is a type of energy that does not create gravity?

To examine this question, we will look for another example of energy that does not exhibit gravity. The photons of the cosmic microwave background were at a black body temperature of about 3,000 °K about 380,000 years after the Big Bang. Today these same photons are at a blackbody temperature of 2.725 °K. Therefore, they have lost about 99.9% of their energy since this earlier time. This "lost" energy did not leave the universe; so where did it go? The answer proposed here is that it became vacuum energy. There was a vastly larger amount of photon energy converted to vacuum energy if we look at the complete history of the universe starting with the Big Bang. Each redshifted photon retained ħ of angular momentum. Therefore the energy transformed into vacuum energy possesses no quantized angular momentum and apparently does not exert gravity. It is proposed that quantized angular momentum is required for energy to exert any force including gravity. Therefore the statement that "*all energy creates gravity"* is proposed to require the following modification: "*All energy* ***with spin*** *creates gravity*." Rather than causing gravity, vacuum energy is the passive energy that gives spacetime its properties and is being distorted (curved) by matter.

The main point of this article has been to establish that GWs encounter a large energy density which supports the vacuum energy model of quantum field theory. A secondary point has been to suggest that vacuum energy is spacetime dipole waves with connections to fundamental particles and virtual particles. However, it is not necessary for the reader to accept any of the proposed connections to dipole waves or fundamental particles in order to acknowledge that vacuum energy has a physical presence in the universe. In this case vacuum energy joins dark matter and dark energy as being physically present in the universe but having unexplained properties.

10 Conclusion

The first detection of a gravitational wave (GW) has important implications beyond cosmology. The experimentally observed characteristics of GW150914 confirm that this 250 Hz GW encountered spacetime as a very stiff elastic medium with impedance of $\mathcal{Z}_s = c^3/G$. The detected intensity was 0.02 w/m^3 and this generated a dimensionless strain amplitude of 10^{-21}. This extremely small displacement of spacetime produced by intensity of 0.02 w/m^2 implies that the GW strongly interacted with a large energy density distributed throughout the vacuum of spacetime. This energy density is not detectable by fermion-based instruments but strongly interacts with GWs. The vacuum energy density encountered by GW150914 would have to be 6.6 x 10^{31} J/m^3 (equivalent to mass density of $\rho = 7.4 \text{ x } 10^{14}$ kg/m^3) to produce the observed strain amplitude, intensity and frequency.

This speaks to the conflict between the vacuum energy predicted by quantum field theory and the critical density of the universe required by general relativity to achieve flat spacetime. GW150914 encountered energy density 10^{40} times larger than the critical energy density of the universe. Extending this to Planck frequency, the difference would be a factor of about 10^{120}. It is broadly assumed by the scientific community that the energy density predicted by quantum field theory must be canceled out by some unknown factor. Now GW150914 offers support to the physical existence of vacuum energy in spacetime. This paper shows that there is actually a connection between the critical energy density of the universe (~10^{-9} J/m^3) from general relativity and the energy density of the vacuum obtained from quantum field theory (~10^{112} J/m^3). The same energy density equation is shown to yield these two vastly different energy densities and give the ratio of these two energy densities as: $\omega_p^2/\mathcal{H}_o^2$. The highest possible frequency permitted by spacetime (Planck angular frequency ω_p) generates vacuum energy density and the lowest possible frequency permitted by the age of the universe (Hubble constant $\mathcal{H}_o$) generates the critical energy density of the universe.

It is proposed that vacuum energy density is real but it is a different type of energy compared to energy in the form of fermions and bosons. Vacuum energy is a passive energy field that gives spacetime its properties. It does not generate gravity; it is the property of spacetime that is being distorted (curved) by mass. GWs strongly interact with this vacuum energy and verifies its existence. Therefore, vacuum energy is the dominant component of the universe. Failing to recognize its existence is proposed to cause numerous mysteries for both quantum mechanics and general relativity. It is suggested that vacuum energy must join dark energy and dark matter as being physically present in the universe but having properties that are not fully understood.

14 References

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